Master’s Thesis

Feasibility Study and Economic Evaluation of a Subsurface Located Deep Geothermal Probe – Drilling into Crystalline Basement

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ABSTRACT

Geothermal energy recovery has become more and more popular during the last decade of high oil prices, and it has been supported by intense research activities. Geothermal energy is characterized as an inexhaustible and continuous source, requires only a small footprint facility and is completely CO_2- and waste-free. The global demand for energy is also believed to increase dramatically in the next few decades, which makes it necessary to introduce further energy supplies to the market, and that, too, in a cost competitive way.

However, geothermal energy systems are more expensive in terms of investment costs per power output gained. Most of the costs are associated with the construction of the wellbore. To make geothermal systems financially more attractive for a broad use in the future and to give an incentive to operators and investors, the total costs must be reduced.

The general idea of this thesis is to utilize existing subsurface facilities, like mines and tunnels, and construct a geothermal recovery system within them. Owing to the existing overburden of the rock, the starting point for the geothermal well is already at an elevated temperature level. The same superior thermal level can, therefore, be reached with a shallower well, compared to an ordinary wellbore drilled from the surface. The amount of overburdening equals the meters of wellbore saved and, hence, leads to lower associated drilling costs.

A general overview of the available geothermal systems is given here, and – based on a project region – the preferable system is chosen. The project region in Styria, Austria, is introduced, and its environment discussed. The existing project mine is evaluated towards feasibility to transport and rig-up a certain drilling rig inside a tailor-made cavern. Suitable drilling rigs for the scope of this project are evaluated, and related HSE aspects are considered.

Furthermore, it is critical to understand the factors that contribute towards cost, their magnitude, and how they influence the economics of the project. Several casing design scenarios are presented and their costs calculated.

Finally, the technical and economic viability is discussed, and the advantages of a geothermal probe located at a subsurface level and potential pitfalls summarized. In addition, recommendations for further projects are given.

KURZFASSUNG

Die Gewinnung geothermischer Energie gewann in den letzten Jahrzehnten durch intensive Forschung und Entwicklung entlang der geothermischen Wertschöpfungskette stark an Bedeutung, bis zuletzt auch durch das hohe Niveau der Ölpreise am Weltmarkt. Energie aus geothermischer Herkunft zeichnet sich durch kontinuierliche Versorgung bei nur kleiner benötigter Grundfläche aus. Zudem ist die Gewinnung CO_2 neutral, abfallfrei und nahezu unerschöpflich. Der globale Bedarf an Energie ist über die nächsten Jahre dramatisch im Steigen begriffen. Um diesen gesteigerten Bedarf zu decken sind weitere, vor allem in technischer und finanzieller Hinsicht konkurrenzfähige Beiträge zur Energieversorgung notwendig. Systeme zur geothermischen Energiegewinnung sind bezogen auf die Investmentkosten pro Energieeinheit teurer als konventionelle Energieträger wie Kohle, Öl und Gas. Ein Großteil der Kosten wird für die Niederbringung der Tiefbohrung(en) aufgewandt. Um geothermische Projekte für die Zukunft finanziell attraktiv zu gestalten, den Investoren einen Anreiz zu bieten, müssen die Gesamtkosten reduziert werden.

Die Grundüberlegung dieser Masterarbeit ist es bestehende Untertagebauwerke einer geothermischen Nachnutzung, im Falle eines Bergwerkes oder einer Nutzung parallel während des Betriebs, beispielsweise in einem Tunnel, zuzuführen. Ziel ist es eine geothermische Tiefbohrung in solch geeigneten Standorten abzuteufen. Die bestehende Überlagerung des Gebirges am Projektstandort sorgt für ein erhöhtes Temperaturniveau am Bohransatzpunkt. Derselbe Temperaturlevel in der Tiefe kann dadurch mit einer kürzeren Tiefbohrung erschlossen werden, im Vergleich zu einer Tiefbohrung ausgehend von der Erdoberfläche. Die Mächtigkeit der Gebirgsüberlagerung entspricht der Länge der eingesparten Bohrmeter und resultiert damit in niedrigeren Bohrkosten.

Ein genereller Überblick der verfügbaren geothermischen Systeme wird gegeben und anhand einer Projektstudie das optimale System ausgewählt. Die Projektregion in der Steiermark, Österreich wird vorgestellt und die örtlichen und geologischen Gegebenheiten diskutiert. Der dort existierende Bergbau wird auf die Durchführbarkeit einer unter Tage Bohrtätigkeit geprüft und bewertet. Bohranlagen mit Firmenstandort in Zentraleuropa werden evaluiert, relevante Aspekte bezüglich Gesundheit, Sicherheit und Umwelt beleuchtet. Des Weiteren werden die Einflussfaktoren einer Tiefbohrung auf die Gesamtkosten anhand mehrerer Modellrechnungen basierend auf unterschiedlichen Verrohrungsszenarien und Bohrtiefen untersucht.

Abschließend werden die technische und ökonomische Durchführung eines solchen Projektes, sowie Vorteile und potentielle Problemstellen betrachtet und Ausblicke für kommende Aufgabenstellungen gegeben.

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1 Introduction

Geothermal energy, as a form of energy, holds promise. Resources are spread globally, in huge amounts, and so supply is indigenous, inexhaustible and supremely continuous. Only small footprint facilities are required to recover geothermal energy, moreover extraction is CO_2- and waste-free. These are only a few advantages of a globally growing source of renewable energy. The global operating capacity reached 12.8 GW in 2015, after 5% annual growth in each of the previous years (Geothermal Energy Association, 2015); the geothermal plants are spread across 24 countries. The total energy provided in the form of electricity and direct heat is estimated at 147 TWh (528 PJ), whereas the ratio between the usage for electricity and heat is 50-50 (REN21, 2015). The most recent data for Austria from 2015 reports a total final energy consumption of 1,090 PJ (Statistik Austria, 2016). Some 15.8% or 172 PJ of the gross energy production is due to renewables (wind power, hydropower, photovoltaic and geothermal energy). Despite the steady growth and availability of resources, only a vast percentage of its potential is utilized. Also, the share of geothermal energy in total electricity capacity and generation remains very low. Only 0.4% of global electricity is generated from geothermal applications (Figure 1).

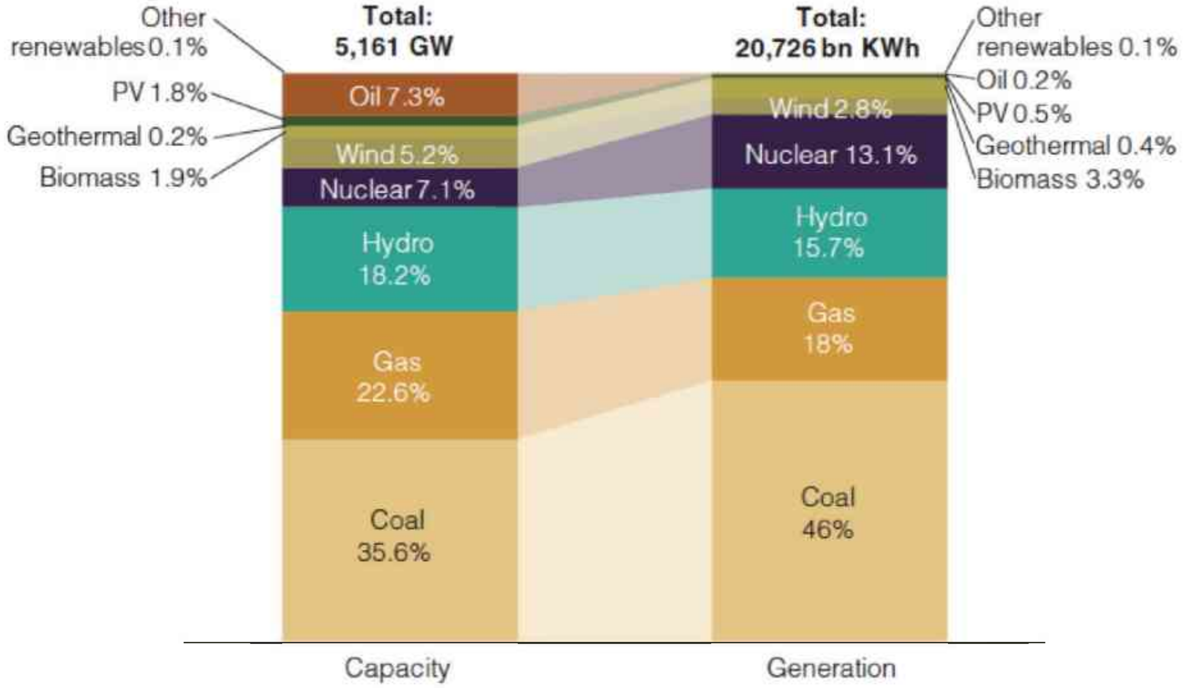


Figure 1: Global installed electricity capacity versus net generation (World Energy Council, 2013)

A forecast from the Geothermal Energy Association (2015) predicts a gain in installed geothermal capacity up to 17.6 GW by 2020 (Figure 2). Currently, around 11.5 to 12.3 GW planned capacity is under development in 80 countries. Thus, geothermal energy recovery is becoming geographically diversified. The largest amounts of installed geothermal electric generation capacity are in the United States (3.5 GW), the Philippines (1.9 GW), Indonesia (1.4 GW), Mexico (1.0 GW) and New Zealand (1.0 GW). The major producers in Europe are Italy (0.9 GW) and Iceland (0.7 GW). By the end of 2014, worldwide there were 612 geothermal power plants in operation. Europe is experiencing a slower development than it could, mainly because of the general lack of awareness of the potential of geothermal energy. Furthermore, funding of such projects is difficult, combined with the exposure to project risk (REN21, 2015).

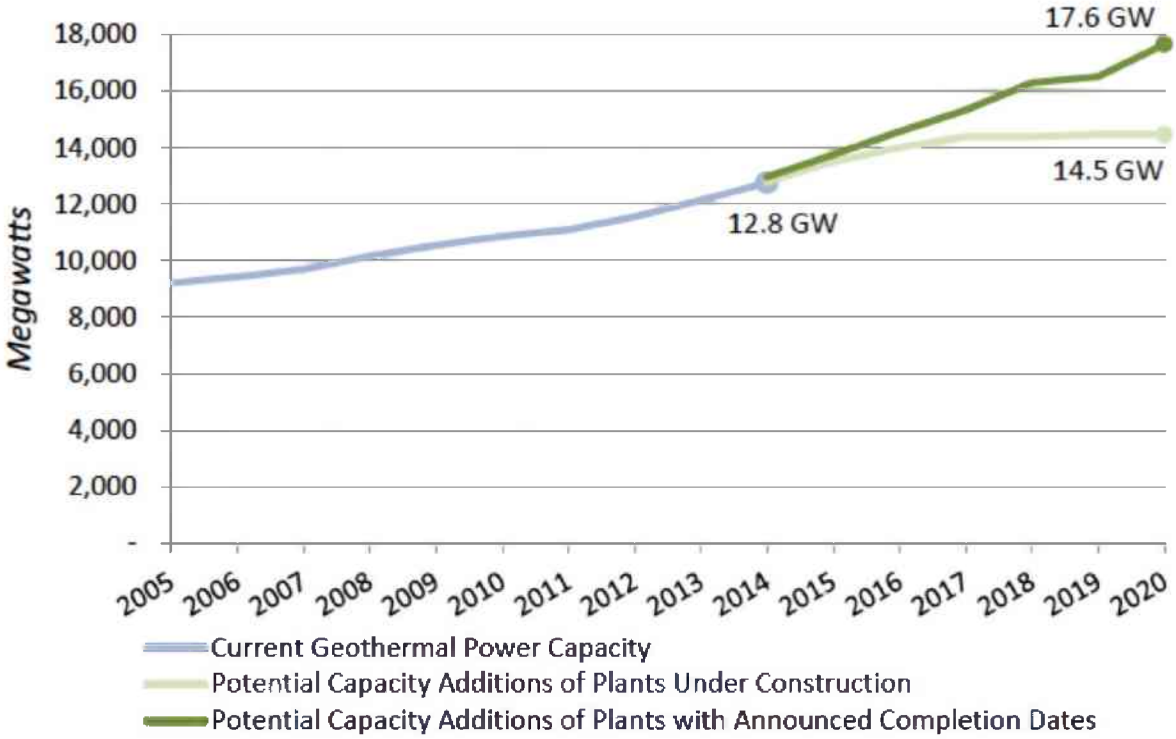


Figure 2: International geothermal nameplate capacity (Geothermal Energy Association, 2015)

Geothermal energy can provide base-load electric power, while having a minimal impact on the environment. Geothermal plants are exempt from the trade of CO_2 certificates within the EU European Union Emissions Trading System (ETS) program (European Commission, 2015). Since no CO_2 emissions are produced the operator need not buy those certificates (at a current price of around 6 EUR per European Union Allowance (EUA) in early 2016), nor invest in technologies to reduce their carbon dioxide emissions. One EUA allows the permit holder to emit one ton of CO_2.

Extraction of geothermal energy is already competitive in terms of costs, compared with other types of renewable and conventional energy supplies, as shown in Figure 3. According to Figure 3, the global levelized costs for geothermal energy are in the range of 65 USD/MWh for flash plants and 100 USD/MWh for binary plants. In comparison, other renewables reach higher values, like wind power (offshore) with 220 USD/MWh, solar power around 250 USD/MWh or various photovoltaic systems with 125 USD/MWh. The only competitive source of energy are small and large hydropower plants, targeting 70 USD/MWh. Nuclear energy, nowadays a highly controversial source of energy amounts to 95 USD/MWh. Owing to the increasing global demand of energy, especially in the non-OECD countries, and the continuing dramatic decline of the oil price, the geothermal energy sector may experience a boost in growth. The biggest share of the overall costs of a geothermal power plant is associated with the construction of the wellbore. Costs for drilling may decrease due to the recent trends in the development of oil prices. Rig count for oil and gas decreased sharply throughout 2015, a continuation of this trend is expected for 2016. The non-employed drilling rigs can be extensively utilized for geothermal drilling. On the other hand, energy generation from oil is economically favorable right now, and, therefore, has the ability to force the more expensive geothermal energy out of the market.

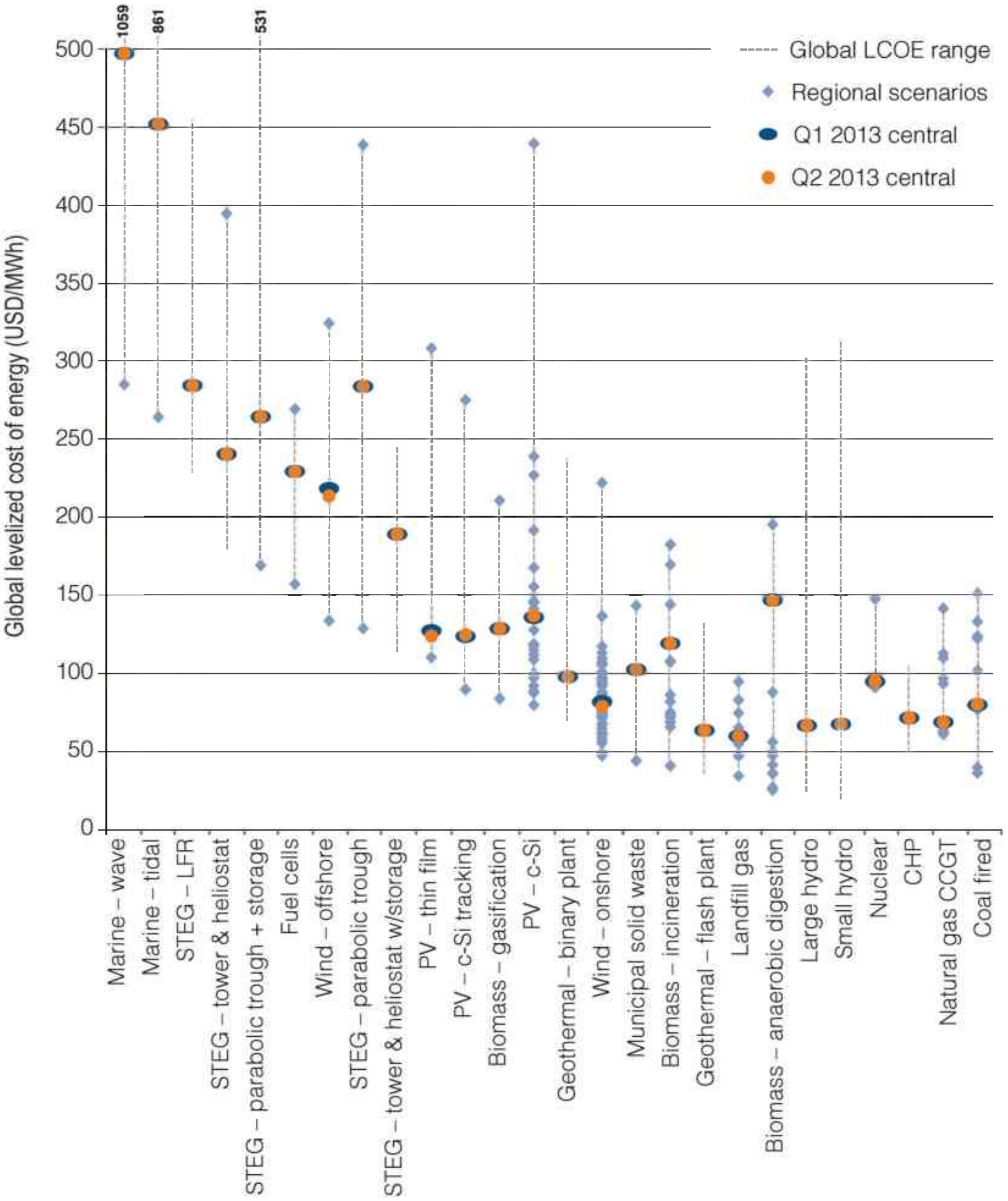


Figure 3: Global levelized cost of energy in Q2 2013 (World Energy Council, 2013)

Seeking innovations in construction of geothermal plants, which would remain at a stable level of costs over decades, is a more favorable way that can be pursued. Such an innovation is introduced, analyzed and evaluated in this thesis. As drilling costs are increasing exponentially with increasing depth, a reduction in the length of the wellbore and thus the drilling time will lead to lower overall costs. To reach the same depth and, therefore, temperature level as with a longer wellbore, the top of the geothermal well must be located at a subsurface level. This, in turn, can be achieved by locating the drilling rig within a mine or tunnel that experiences a significant overburden of rock.

1.1 Limitations of Geothermal Energy Recovery

To date, the majority of geothermal wells around the globe have been drilled and operated in areas of high heat flow. High subsurface temperatures are favorable for geothermal energy recovery. Such areas are found, for example, along the Ring of Fire in the Pacific Ocean, the mid-ocean ridge, especially Iceland, and in sedimentary basins. At those places, geothermal energy extraction takes place extensively with limited need of energy conversion systems. The geothermal fluid, which delivers the subsurface heat to the surface, has a high enough temperature to power a single-flash power plant and serve for electricity generation. Nevertheless, geothermal energy can be extracted theoretically everywhere in the world, its just a question of the prevailing heat flow and how to make use of the recovered energy. In order to utilize a geothermal well for electricity generation or to elevate the level of thermal energy, a certain temperature level at depth is required. Since drilling operations are technically limited to certain depths and drilling costs increase non-linear, means progressively, with depth, an upper limit is reached up to which a geothermal well is economical. Within the scope of this work, a solution for this problem is proposed and evaluated.

1.2 Objective

Main objective:

To identify whether geothermal energy can be recovered from already existing subsurface facilities in a technically feasible, safe and economical manner. Subsurface facilities like caverns or tunnels favorably indicate significant overburden rock. This overburden can lightly exceed several hundreds to thousands of meters of rock. An elevated temperature present in the underground would reduce the length of a subsurface drilled wellbore, but would target the same temperature level in depth. Thus drilling from a subsurface location can contribute towards lower overall costs for a geothermal project, compared to a conventional one from the surface.

Secondary objectives:

- Gather the current knowledge of geothermal drilling operations
- Examine of logistics governing the transportation and supply of a subsurface operating drilling rig
- Analyze HSE considerations arising out of subsurface drilling operations
- Execute an economic evaluation of a subsurface drilling operation, compared to conventional drilling operations from surface

2 Geothermal Energy

Before explaining the different kinds and applications of geothermal energy systems, a general valid definition must be introduced. Geothermal energy is energy produced by utilizing natural sources of heat deep below the Earth's surface (Massachusetts Institute of Technology, 2006). Versatile advantages are characteristic of geothermal energy: inexhaustible and efficient supplies of energy; its climate-friendly nature due to carbon dioxide-free extraction; capability to supply base load power, independent of weather conditions; full day availability; independence from fossil fuels, which encourages the regional net value added; future-proof; and low-footprint environment.

The structure of the Earth is shell-like (Figure 4). Beginning from the center, the Earth consists of the inner core, which is supposed to be liquid, enclosed by an outer core, which is solid, with mantle and crust as the outermost shell. Some 99% of the earth's volume is hotter than 1,000°C, only 0.1% is colder than 100°C. Hence, there is a huge amount of heat stored inside the Earth.

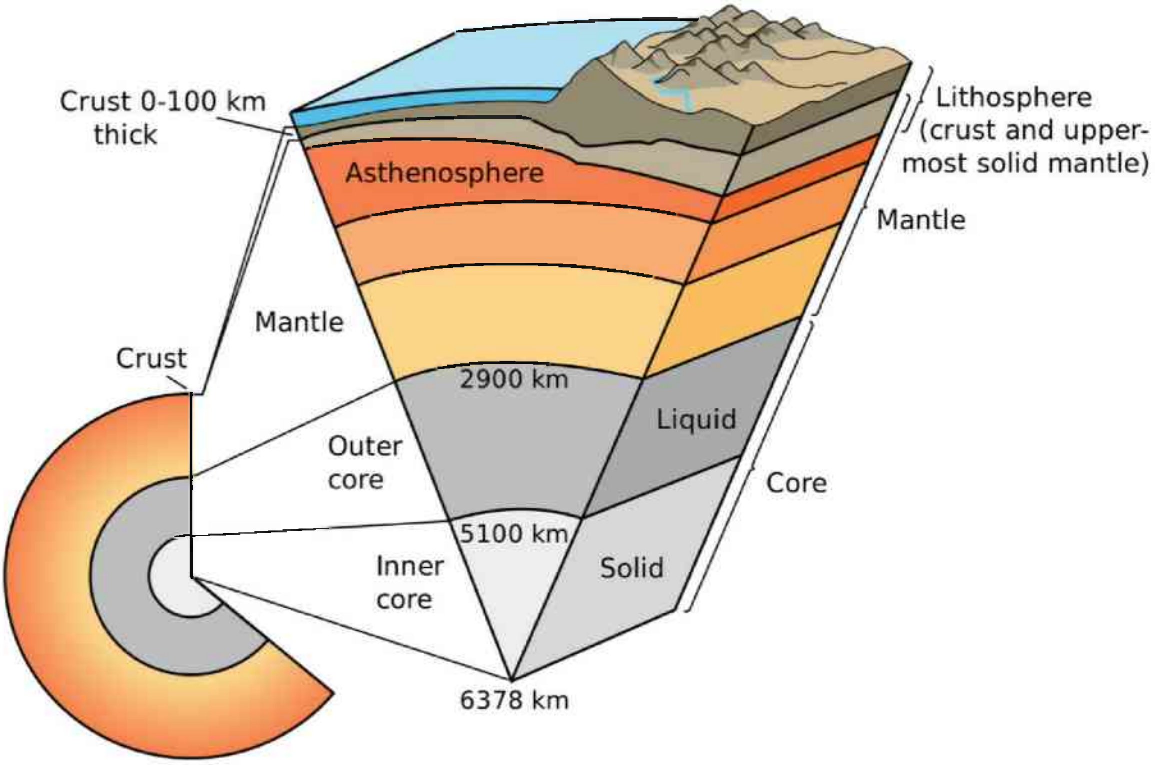


Figure 4: Structure of the Earth; cutaway from core to crust (Wikipedia, 2016).

In the inner core, pressures of around 4 million bar and temperatures over 5,000°C are assumed to be present. The average global surface temperature is 14°C. As a consequence, heat flows from the spot with higher temperature potential, which is the inner core, to the spot with lower potential, which is the Earth's surface. This terrestrial heat flux causes the Earth to lose heat over time. From a global perspective, the average heat flux is 65mW/m^2. Approximately 30% of the heat flux is due to the heat coming from the inner core. The other

70% is generated on a continuous basis in the crust. Driving forces for this heat generation is the radioactive decay of mainly three naturally occurring elements, Uranium (^{238}U, ^{235}U), Thorium (^{232}Th) and Potassium (^{40}K). In sum, they provide around of 40 million MW of thermal energy.

A closer investigation of the Earth's crust shows that the mineralogical composition varies worldwide. Also, the thickness is not unique. Acidic rocks, like granite, are denser, and have a higher heat production than other rocks. The continental crust is made up of those rocks. In contrast, the oceanic crust comprises of mainly alkaline rocks, e.g. gabbro. The difference in the composition of the crust causes differences in heat heat flux' at different locations. Figure 5 shows the surface heat flow distribution in Austria. Deducting the total heat flux at a certain location, it is the sum of the constant heat flux from the inner core plus the variable heat flux in the crust. Temperature and heat anomalies can also result from to the presence of fluids on the subsurface, as it is the case in the mid-ocean ridge and in volcanic regions.

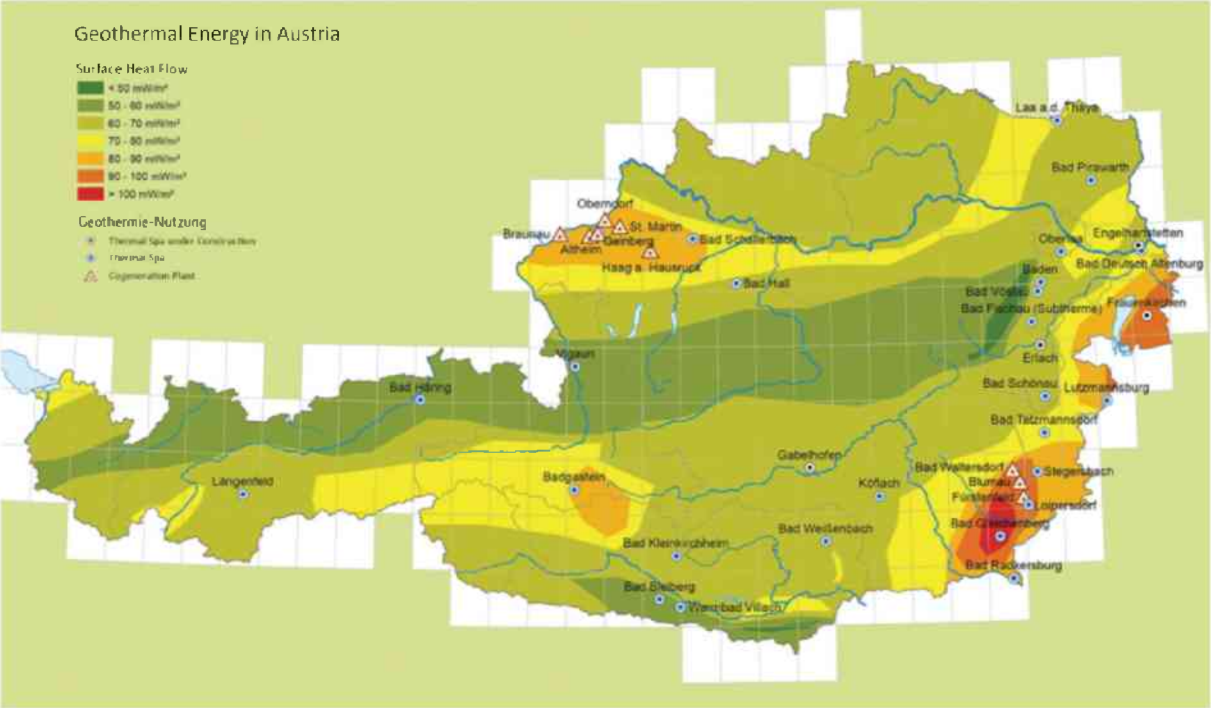


Figure 5: Map of surface heat flow in Austria (Geological Survey of Austria, 2016).

Preferred areas of high heat flow are the Molasse Basin in Upper Austria, the Vienna Basin in Lower Austria and the East Styrian Basin in Styria and Burgenland. These Basins are geologically younger, compared to the other prevailing lithologies in Austria, hence, they provide a high heat flow. Owing to volcanism, the region in the East Styrian Basin shows the highest heat flow with values above 100mW/m^2. With increasing distance from the mentioned basins towards the Alps, the heat flow is gradually decreasing down to values even below 50mW/m^2.

Heat transport

Information about the physical properties of the lithology are the basis for a successful design of geothermal energy recovery systems. Of major interest are properties that influence the transport and storage of heat. Thermal conductivity, heat capacity and heat production are the most relevant properties that have to be included in an analysis. Thermal conductivity and heat capacity are depended on pressure and temperature. If, also, there are fluids present, porosity and permeability of the formation are required in addition. Moreover, physical properties of the thermal water — such as density, viscosity and compressibility — are of interest.

Heat transport can take place in various ways. Geothermal energy can be transported either by conduction or by convection. Convection occurs due to movement of fluids, for instance thermal water in aquifers. Conduction is the prevailing heat transport mechanism in solids. The heat flux through rocks is not constant; rather, it is diverse. Crystalline rocks (e.g. granite, gneiss) conduct heat two to three times better than sedimentary rocks (e.g. sandstone, conglomerate). This is mainly due to the different rock properties, their mineralogical composition and anisotropy effects. Essential for the heat transport is the presence of hollow spaces in the formation and the way in which they are filled. Air acts like an insulator for heat transport, whereas water has marginal inferior transport properties than average rocks. In conclusion, the karstification and presence of aquifers exercise a major influence on heat transport.

Geothermal gradient

As a generally valid rule, temperature increases with depth. However, the magnitude of increase is not constant over depth, and also varies over different geographic locations. The thermal conductivity (λ) [W m^{-1} K^{-1}] and heat flux (q) [W m^{-2}] of different rock types are responsible for this behavior.

$$q = \lambda \cdot \nabla T$$

The average geothermal gradient — the difference in temperature between two depth points — is in the range of 2.8-3°C/100m in Central Europe. Deviations from the mean geothermal gradient result respectively from temperature and heat anomalies, respectively. Examples of positive anomalies, where the geothermal gradient is higher, and hence more favorable for heat extraction, are volcanic regions (e.g. islands), uprising deepwaters, formations with higher thermal conductivity (e.g. salt domes) or areas with increased geo- or biochemical heat productivity. Such regions are preferred for geothermal wells, since a higher temperature level can be accessed in shallower depths compared to regions with a standard geothermal gradient.

There do exist several methods for extracting energy from geothermal resources. Depending on the depth of the water reservoir and thereof the reservoir temperature, several opportunities in terms of geothermal systems can be considered for harnessing geothermal energy. But it is not only the depth and temperature regime that are crucial; the rock formation needs to have sufficient permeability, and, to be most favorable, must be a naturally fractured reservoir. It is only with these requisites that energy production is feasible. In case no natural fluid is present in the rock formation present, the implementation of a geothermal system is also possible. The fluid that is needed to transport energy must then be injected into the desired zone of high heat flow, and reproduced after a heating period. Such systems are called engineered (or enhanced) geothermal systems, or EGS in short.

2.1 Near-Surface Geothermal Systems

For near-surface geothermal systems a distinction between open and closed systems is made. In closed systems, the circulating fluid experiences no contact with the formation, it flows through the inner pipe and the annulus. Whereas in open systems, the formation is part of the flow path. Near-surface systems usually target a depth of several meters up to a couple of 100's meters below surface. Their maximum depth is approximately at 150m; deeper applications do no longer return value for money. With a standard geothermal gradient of 3°C/1000m the expected temperature is, ordinarily, 25°C. The most common types of near-surface geothermal applications are ground heat collectors, borehole heat exchangers and energy piles. When appropriate temperatures are reached, this list can be extended by waste water-, mine water-, and tunnel water utilization.

Ground heat collector

Pipes with a length of up to 100m are laid in a very shallow manner into the soil, right up to 5m depth. According to their arrangement in the soil, they are referenced to as horizontal ground collectors or geothermal baskets, if the individual helix-shaped pipes form a basket.

Borehole heat exchanger (Geothermal probe)

Vertical wellbores up to 400m in depth circulate a medium, which can be pure water, a water mixture, or gas, and thereby gather the heat from the formation. Most commonly, boreholes reach a depth of 100m on an average. Borehole heat exchangers are technically mature.

Energy piles

One or more reinforced concrete piles with incorporated double or fourfold U-shaped pipes supply a heat pump. A network of polyethylene pipes can be used as an alternative. The pipes cover a large volume by applying multiple coils in the concrete pile, in order to compensate for the shallow depth that they are spudded into the ground. This is the major differentiation to a borehole heat exchanger, where only one extensive flow path exists. Concrete, together with steel inserts, is the most commonly used material for piles, since it shows great stability and for the use as energy piles, also sufficient thermal conductivity (similar to sandstone, marginally lower than crystalline rocks).

All the near-surface geothermal systems discussed above require a heat pump for the uplift of the thermal level.

2.2 Deep Geothermal Energy Recovery

The target depths of deep geothermal systems reach higher temperature levels in comparison to near-surface geothermal applications; hence, the energy output is higher. Not only is the temperature level is higher, it is also constant, compared to near-surface depths. Up to a depth of 20m, the soil is affected by the influence of day and night; solar radiation heats up the soil during daytime. During night, the formation cools down.

2.2.1 Hydrothermal Systems

Low enthalpy systems

Hydrothermal systems are based on the utilization of hot water originating from an aquifer. Instead of an aquifer, a highly permeable fault zone can also be utilized for circulation. The extraction takes place in a direct manner, or via a heat pump. The primary application field is the feeding of local or district heat networks. Industry and agriculture nearby are further consumers. There are several options for using the thermal energy produced by the hydrothermal geothermal system. Most common is the utilization for electric power generation, followed by direct use in process and direct-heating applications. There is also a possibility of combined heat and power generation in hybrid systems. For deep geothermal probes, the usage of heat pumps promises energy savings. The decision, which system to use, depends mainly on the type of geothermal systems, either deep geothermal probe or EGS. For further distinction the temperature at the desired depth is crucial (Massachusetts Institute of Technology, 2006).

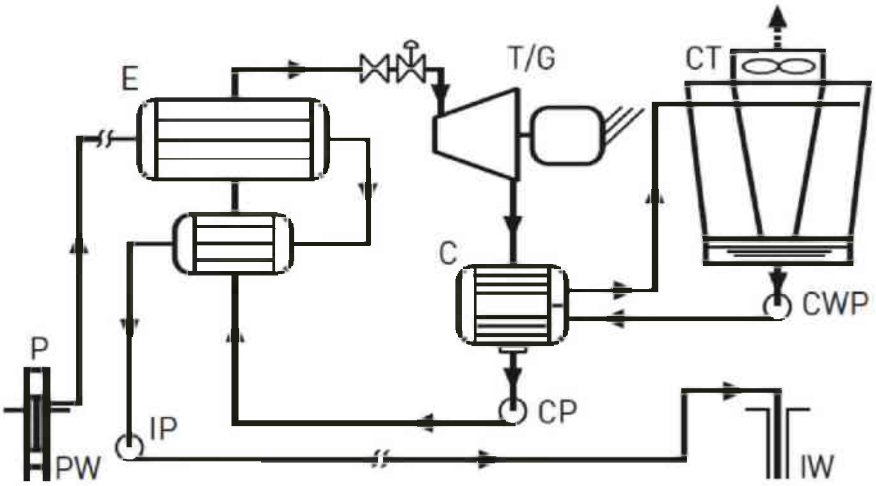


Figure 6: Binary power plant (Massachusetts Institute of Technology, 2006). PW production well; P pump; IP injection pump; E heat exchanger; T/G turbine/generator; C condensator; CP compressor pump; CWP cold-water pump; CT cooling tower; IW injector well.

Binary power plants (Figure 6) are ideally suited for energy recovery from geothermal wells. They have sufficient efficiency to utilize low- to moderate-temperature geothermal fluids. The water that is circulating through the geothermal well is passed through a heat exchanger where it transfers its heat to another liquid. This liquid is of lower boiling point than the water from the geothermal system and, thus, flashes from liquid to gaseous phase with more ease. The generated stream is fed in a gas turbine for electricity generation. After the turbine/generator unit, the steam passes a condenser that incorporates a cooling tower, which cools the steam until it reaches a liquid state. Then, the liquid flows back to the heat exchanger. The well fluid that flows through the heat exchanger is pumped back into the injection well by an injection pump.

Above a temperature of 80°C the operation of an Organic Rankine Cycle (ORC) plant can be considered. The central piece of an ORC plant is the organic circulation medium, either iso-pentane, butane or propane. Those hydrocarbons vaporize at a relatively low temperature. Most frequently used as a working fluid is an ammonia-water mixture (Kalina cycle). The Kalina process can efficiently be used at water temperatures above 120°C. A mixture of two substances — ammonia and water — is used as a working fluid. Characteristic for this mixture is a non-isothermal vaporization: the temperature increases during the process.

The loss of energy is a ubiquitous issue in geothermal systems, especially when using technologies to enhance the overall efficiency of the system. Part of the recovered energy is lost due to reentry into the Earth, while cooling processes release additional energy into the surroundings. Losses in the turbine and the own use of energy for the plant complete the bill.

A common application for low-enthalpy systems is the hydrothermal doublet. Hot water is produced from a producer well. On the surface heat is extracted via a heat exchanger. Since not all of the heat flux can be mobilized, residual heat remains in the water. The cooled-down water is injected into the same aquifer from which it originates from by an injection well. Reinjection has also other reasons: pressure maintenance is provided; the aquifer is — so to say — recharged. Owing to high mineralization of the formation water, a different kind of fluid cannot be easily injected, since it would alter the characteristic of the formation water. Therefore, injection of the same water type is the most appropriate solution, and at the same time, the most economic and convenient option. The bottomhole distance between the wells should be in the range of 1,000 to 2,000m. Exact spacing can be determined by model simulation of the entire geothermal system along with geology. If the spacing is too narrow, a thermal bypass may result, and the feed water will cool down. On the other hand, if the spacing is too wide, there will be no hydraulic support from the injected water. For lifting of the water out of the well, either an ESP or a sucker rod pump is used.

High enthalpy systems

Under special circumstances (e.g. in a deep granitic basement rock, magmatic intrusions) in-situ temperatures may range from about 250°C to more than 500°C. For the lower end of the range single-flash or double-flash power plants are utilized, above the critical temperature (374°C) and pressure (22MPa) of the geofluid triple-expansion power plants are used for supercritical EGS fluids. In a single-flash power plant (Figure 7), wet steam is first separated into steam and water, and then the steam is used to drive a turbine before pumping into a cooling unit. For a double-flash power plant, the water that has not flashed in the first cycle is transferred to a lower pressure tank. There, it is again subject to flashing. There is also the option for a supercritical single-expansion plant, those have to handle ultra-high inlet pressures (Massachusetts Institute of Technology, 2006).

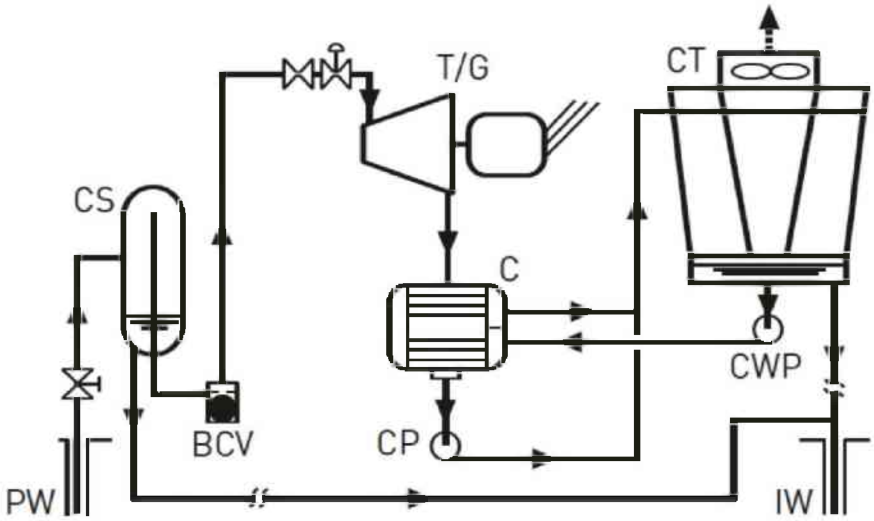


Figure 7: Single-flash power plant (Massachusetts Institute of Technology, 2006). PW production well; CS compression separator; BCV back compression valve; T/G turbine/generator; C condensator; CP compressor pump; CT cooling tower; CWP cold-water pump; IW injector well.

2.2.2 Petrothermal systems

Petrothermal systems form the second group of systems for deep geothermal energy recovery. They are independent of aquifers since they recover the heat stored in the formation around the borehole. Common systems are available under the synonyms Hot-Dry-Rock (HDR), Hot-Wet-Rock (HWR), Hot-Fractured-Rock (HFR), Deep-Heat-Mining (DHM) or Enhanced-Geothermal-System (EGS). EGS is nowadays the most frequently used term.

Enhanced-Geothermal-System

The main purpose of EGS is electricity generation. High formation temperatures of approx. 200°C are aimed at. To attain such high temperatures, locations with high geothermal gradients are necessary. A deep wellbore, with a depth between 5,000 and 7,000m, is a must. As a consequence of this great depth, the lower section of the wellbore is drilled into crystalline basement rock. These crystalline formations are naturally fractured and water, which is also the circulating fluid, can flow through the formation. To enhance the flow behavior, the rock permeability is maximized by hydraulic fracturing. Like a hydrothermal doublet the EGS consists of a production and an injection well (Figure 8). Between the injection well and the production well, the water flows trough the fractures and draws heat from the formation. As EGS is independent of the existing aquifers, such a system can theoretically be installed everywhere. However, high geothermal gradients and suitable geology are an advantage.

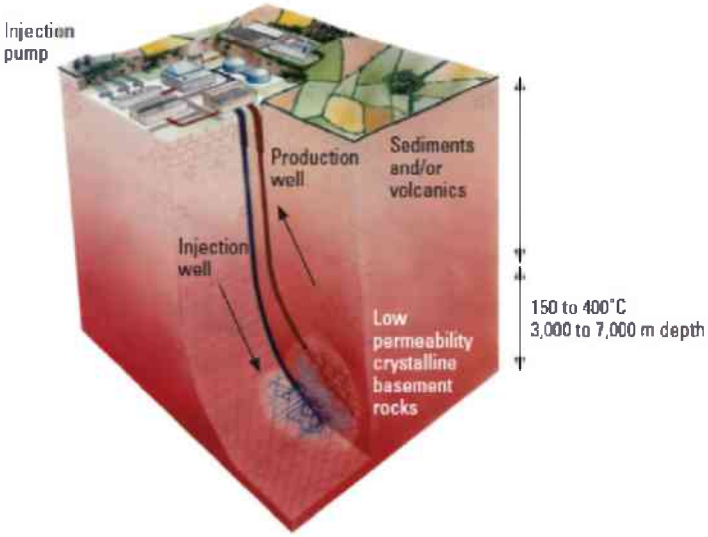


Figure 8: Schematic of an EGS (Massachusetts Institute of Technology, 2006).

Deep geothermal probe

This type of petrothermal system uses a closed circulation system in a single wellbore (Figure 9). Deep geothermal probes serve only for heat supply; electricity generation is not feasible with the state-of-the-art technology due to low heat recovery. Recovery is lower than in other systems, mainly due to the low surface area, where heat can be transferred from the surrounding formation to the circulating medium. The formation cools down over time because of the heat extraction, which very slowly decreases the performance of the system. The fact that it can be installed theoretically everywhere, like an EGS, is beneficial for the use of a deep geothermal probe; moreover, there is no risk of environmental pollution or chemical reactions in the formation due to the circulation within a closed system in the wellbore. Also, hydraulic fracturing operations should not be conducted.

The deep geothermal probe (or borehole heat exchanger) consists of two concentric pipes — a coaxial system. Those pipes create two flow paths, one between the inner diameter of the outer pipe (casing) and the outer diameter of the inner pipe (tubing); the other path is inside the tubing. The circulating medium is injected at a certain temperature in the casing-tubing annulus and is heated up — due to the increasing formation temperature — while flowing down the wellbore. The maximum temperature is reached at the bottomhole depth. This temperature should be conserved while the fluid is traveling inside the tubing back to the surface.

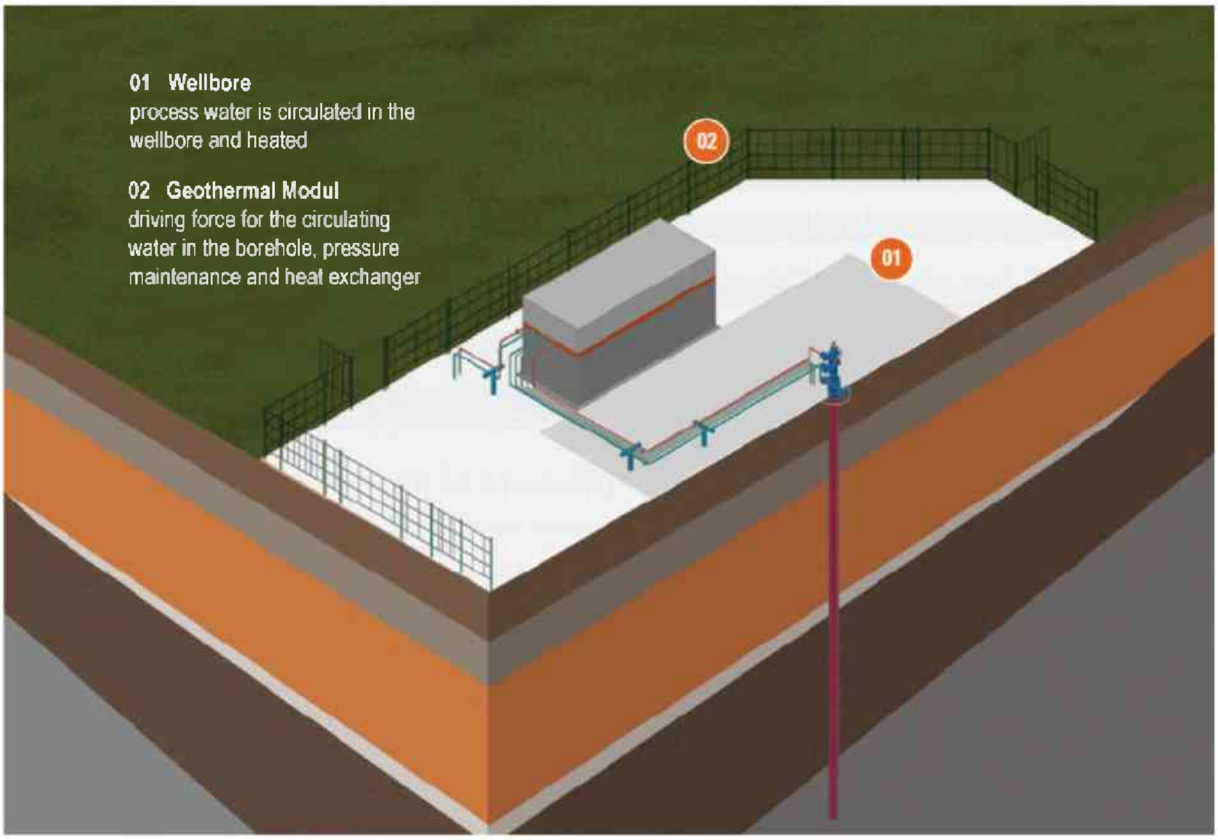


Figure 9: Deep geothermal probe modified from RAG (RAG Rohöl-Aufsuchungs Aktiengesellschaft, 2013).

The heat output of the system is dependent on the depth of the wellbore, diameter of casing and tubing, geothermal gradient, properties of the rock, kind of tubing (including isolation) and on thermal conductivity, in general. The uppermost part of the borehole should have a completion with low thermal conductivity, while the middle-to-lower part must have a high conductive completion in order to maximize energy recovery. Compared to hydrothermal systems or EGS, the energy output of deep geothermal probes is significantly lower. On the other hand, the investment cost for these systems remains at a high level. A deep geothermal probe requires only minimum maintenance and has low operating costs.

2.3 Reference Projects for Deep Geothermal Probes

Till date, only a few borehole heat exchangers have been implemented, and the most of them in Europe. The outcome of those projects can be best described as mixed success (Okech, Liu, Falcone, & Teodoriu, 2015).

The deep borehole heat exchanger in Weggis, Switzerland, reaches a depth of 2,300m with a bottomhole temperature of 78°C. In operation since 1994, the well delivered 220 MWh(thermal) per year from 1995 to 2000 for purposes of direct heating and for heat pumps. Up to a depth of 1,902m, a 7” casing was installed, with a 5 1/2” liner completion for the final depth. As production tubing, a double vacuum-isolated pipe was selected for the first 1,780m, complemented by an uninsulated pipe from 1,780 to 2,295m.

Another project from Switzerland, in Weissbad, utilized an existing borehole of 1,600m depth. The well was originally designed to supply a spa and hotel complex with thermal water. Since the target layer turned out to be a tight formation, the well was used as a geothermal probe instead. The bottomhole temperature of 45°C was too low to allow for economic operations of the BHE.

A 2,500m-deep geothermal probe was designed and implemented within the SuperC project of the RWTH Aachen in Germany. The well was drilled in an urban area, next to a university building, which, in turn, should be heated and cooled by the geothermal well. The concentric injection/production pipe system, with the inner tube made of glass fiber-reinforced plastic, reached a bottomhole temperature of only 35°C, instead of the planned 60°C. Accompanied by several technical problems, the project was declared a commercial failure in 2014.

The well Mühlleiten 2 (ML-002) in the municipal area of Neukirchen a. d. Vöckla, Austria was originally planned to serve for production of oil and gas. The Austrian company RAG finished drilling in 2009 and since oil and gas production was not economic, the well was considered as a potential geothermal well. The well features a temperature of 105°C in 2,850m depth. In 2012 the wellbore was recompleted as a deep geothermal probe. Via a 1,000m underground pipeline the extracted heat is transferred to a biomass heating plant and delivering sustainable energy for around 100 households. The maximum yearly heat output is 3,500MWh, while saving 450tons of CO_2 emission (RAG Rohöl-Aufsuchungs Aktiengesellschaft, 2016).

All of the existing deep geothermal probes, including the three examples above, have a maximum depth of 2,500m, with a maximum heating capacity range of between 500kW and 750kW (thermal) in common. They are all limited to heating and cooling applications. Moreover, research has unveiled a significant imbalance between CAPEX needed to realize such projects and the gained revenue gained from thermal output. Drilling costs would have to be far lower, and the efficiency of the system and electricity prices higher, to achieve an economically viable base (Okech, Liu, Falcone, & Teodoriu, 2015).

3 Project Region

In order to cope with the idea of a geothermal probe located deep in the subsurface and to determine the possible outcomes of such a project, a suitable active mine must be selected. Such an active mine is found in a side valley between the cities of Graz and Bruck a.d. Mur located in Styria, Austria.

3.1 Geothermal Potential

The mine's main objective is to mine magnesite. Over the years, galleries a couple of kilometers long were dug into the rock formations. The lowest point in the mine is approx. 1,000m below surface, which is equal to 250m above sea level. Owing to the continuous mining operations, extensive information was gathered about the geological formations around the magnesite deposit, namely the Hacksteinerformation. Seismic measurements of the area where conducted by the Montanuniversitaet Leoben and Joanneum Research in 2008, though the three seismic profiles target only a depth shallower than 1,000m, where the magnesite deposit is located. Hence, they are not indicative of deeper layers and structures. The deeper lying crystalline basement rock can be tracked to surface in other regions of Styria, for example in the Gleinalm region, where a massive thickness is encountered. It can, therefore, be concluded that the formation below the magnesite body is a homogeneous crystalline basement.

Figure 10 shows the depths of the 150°C isotherms of the project region, determined within the scope of the Transenergy project (Transenergy, 2013). The isotherm closest to the project location is at a depth of 4,900m below the surface. Considering an average surface temperature of the most central city in Styria, Leoben, of 9.9°C (Land Steiermark, 2016), the estimated bottomhole temperature of a 6,000m deep borehole is approx. 180°C.

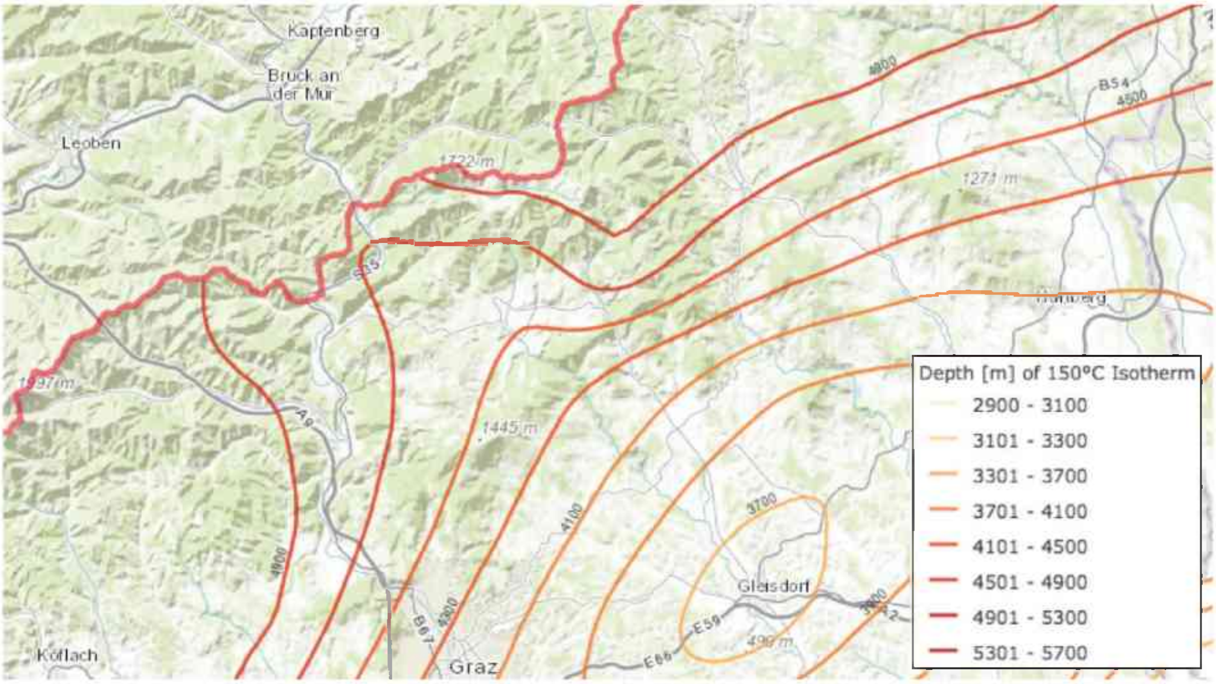


Figure 10: Depth of 150°C isotherm (Transenergy, 2014).

3.2 Rock Properties

Several rock samples taken from the project location as well as from a remote, but geologically identical location were analyzed to gather information about the affected geological layers for the construction of the cavern and the drilling operation.

3.2.1 Hacksteinerformation

The Hacksteinerformation, part of the Laufnitzdorfgruppe, is an approximately 70 – 120m thick geological formation. Clay and siltstone are the dominating minerals in the formation, with inclusions of vulcanite, feldspar-rich sandstone and dolomite. Embedded in the Hacksteinerformation is the magnesite deposite, with a total length of 2,000m and a vertical spreading from 800m to 240m above the sealevel. Rock samples taken by the mine operator show a rock strength, unconfined compressive strength (UCS), of 99.2 – 136.4MPa in the foot wall. Samples taken parallel to the foot wall reveal a reduced rock strength (UCS) of 68.2 – 74.9MPa. In contrast, the hanging wall has rock strengths < 10MPa. A study indicated that 80% of the cavern can be constructed in the more stable, claystone-rich, part of the foot wall. Further rock samples, taken by the Montanuniversitaet Leoben, showed UCS values from 52.9 to 109.4MPa in the target location for the cavern. Samples were taken each from the rugged, fractured part of the formation and the non-faulty part. The rock density is uniform 2.72 g/cm^3.

3.2.2 Crystalline Basement

No detailed information about the crystalline basement is available directly within the project region, although seismics were shot. Those seismics targeted only the magnesit deposit, which is located in a shallower depth. To obtain rock properties, the formation was traced back to the Gleinalm tunnel, where rock samples were taken. Mechanical tests of this samples have shown UCS values from 92 to 279MPa and an average value of 169MPa. The rock density was estimated with 2.9 g/cm^3.

3.3 Infrastructure

The mine is easily accessible by heavy haulage from the highway S35. Through the connecting road between the highway and the mine is curvy, a trouble-free transportation of the drilling rig is ensured. Sufficient storage area for supply trucks and equipment is available in close proximity of the mine, on the property of the mine operator.

The access road inside the mine to the target well location is in good condition and is paved. The gallery network of the mine has a total length of 2,900m and a maximum inclination of 12%. Chapter 4.5 undertakes a detailed investigation of the gallery network. Water and energy supplies can be provided along the galleries to the endpoint, or over an already existing supply shaft. The shaft has the advantage that it is separated from the main galleries and, therefore, cannot be affected by the potentially dangerous actions taking place in the galleries. On the other hand, a leaking supply pipe will not directly influence the operations, and does not imply a safety risk.

4 Wellbore Construction

This chapter explains in detail the considerations in planning the wellbore.

4.1 Desired Wellbore Depth

An evaluation of the optimum depth for geothermal usage is the starting point for a successful outcome of the project. Temperature is steadily rising with the increasing depth of the wellbore; hence, an infinitely deep wellbore would be the best option. This desire cannot be satisfied by the state-of-the-art in drilling technology, as drilling operations are limited to certain depths. These depths depend mainly upon geological factors, like increasing pressure and abrasiveness of the formation with depth. Drill bits are somehow limited to physical boundaries and the wear of the tools will increase to non-tolerable amounts. The drilling rig is also restricted by technical limitations, citing the torque of the topdrive and the hookload capabilities. With these pieces of information, a compromise for a drillable and thermally rewarding depth must be found. For the scope of this work, a target depth of 6,000m below surface is defined. According to the geothermal potential (3.1) in the project regions a bottomhole temperature of 180°C can be estimated, which is sufficient for energy recovery. Moreover, due to the 1,000m overburden, the wellbore needs to be just 5,000m long. This depth and hence hookload capacity is within the specification of most available drilling rigs.

4.2 Selection of a Suitable Drilling Rig

The criteria for the selection of a suitable drilling rig for operation in a mine are based on particular requirements. The excavation of a cavern, which is appropriate for the placement of the drilling rig, is time-consuming and requires high technical and financial efforts, if the excavated material cannot be used as a natural resource. Moreover, geological conditions and geomechanics have to be considered. Accordingly, the drilling rig with the smallest height and footprint must be prioritized in the selection process. To gain sufficient temperature for the geothermal usage, the target true vertical depth (TVD) of the wellbore must not be below 5,000m. Hence, the maximum capacity in terms of drilling depth should exceed this depth. Concerning the power supply, it has to be taken into account that fuel-, or gas-powered electricity generators can only be used under certain limitations. The hazard potential through ignition or explosion of fuel or other flammable liquids in a closed, subsurface space is very high. In addition, air ventilation and extraction of the emerging fumes must be taken into consideration. Drilling rigs with external power supply — via the power grid — are preferred. Furthermore, a drilling rig that is operated on the subsurface needs to process the drilling mud in a closed system. An occasionally occurring gas must not escape into the free atmosphere, otherwise it may inflame. Consequently, the drilling rig must have such a system.

The following drilling rigs, all originating from Central Europe (Germany, Austria), were compared:

- Bauer TBA 200 Deep Drilling Unit
- Bauer TBA 300 Deep Drilling Unit
- Bentec EURO RIG 350t
- Herrenknecht Vertical Deep Drilling Rig Terra Invader 350 Slingshot
- Herrenknecht Vertical Deep Drilling Rig Terra Invader 350 Box-on-Box
- Max Streicher Tiefbohranlage VDD370
- RAG Energy Drilling Bohranlage E200/E202

Table 1 summarizes the technical data of the compared drilling rigs that have been compared.

	TBA 200 Deep Drilling Unit	TBA 300 Deep Drilling Unit	Bentec Euro Standard Rig 350 t	Herrenknecht Terra Invader 350 Slingshot	Herrenknecht Terra Invader 350 Box-on-Box	Max Streicher VDD370	RAG E200/202
Hookload	200t	300t	350t	350t	350t	336t	250t
Max. Hookload						377t	300t
Max. Drilling Depth	3000m	5000m	6000m	5500m	5500m	5000m	5500m w/ 3 1/2" DP
Power Supply	n/s	oder 4x1MW diesel generator	n/s	max. 1540kVA per generator	max. 1540kVA per generator	4x852kW AC generator	6x532kW diesel generator
via grid	n/s	20kV	n/s	possible	possible	possible	n/s
Footprint	30m x 28m 840m2	33m x 23m (*2) 759m2	55m x 40m 2200m2	n/s	n/s	1224m2	85m x 43m (*1) 3655m2
Total height	33m	41m	44m	46m	52m	31m	41m

Table 1: Comparison of technical data of selected drilling rigs. (*1 Dimensions originate from a standard blueprint, with space optimization not being considered, *2 If the diesel generator and tank are not included, the width of the footprint is reduced from 41m to 33m)

According to the technical data and the particular requirements, as previously described, a selection was made. The ranking is based on the fulfillment of following four major aspects: (a) Small footprint, (b) low total height, (c) capability of drilling a 5,000m well and (d) possibility of external power supply.

1) Bauer TBA 300 Deep Drilling Unit

The Bauer TBA 300 Deep Drilling Unit is convincing, with the lowest footprint requirement. The rig is capable of drilling the required target depth and can handle the corresponding loads. A possible power supply via the local grid is also favorable. The Bauer TBA 300 Deep Drilling Unit can also be ordered with a self-erecting derrick; only a crane for unloading of the transport units is required.

2) Max Streicher Tiefbohranlage VDD370

The VDD370 from the manufacturer Max Streicher shows similar performance data as the drilling rig from Bauer. However, the required footprint is larger.

3) Herrenknecht Vertical Deep Drilling Rig Terra Invader 350 Slingshot

Herrenknecht does not provide information about the needed footprint required. A major reason why the rig is nevertheless considered is its special construction. The slingshot system promises a rig-up of the derrick without the need of a crane; the derrick erects itself. This can be a crucial benefit in the case of the restricted space in a subsurface cavern. A crane is required, however, for unloading of the transport units from the trucks is required though. Moreover, the nominal maximum drilling depth is 500m deeper, as in the two above rigs.

If the footprint of the RAG E200/E202 drilling rig can be drastically reduced for subsurface usage, this rig can be included in the above list.

4.3 Well Location

The top of the wellbore is not, like conventional wellbores, on the surface, but rather at the end of an existing gallery in a specially constructed cavern. An actual overburden of around 1,000m is present above the mine (Figure 11). The well is located around 250m above sea level (SL).

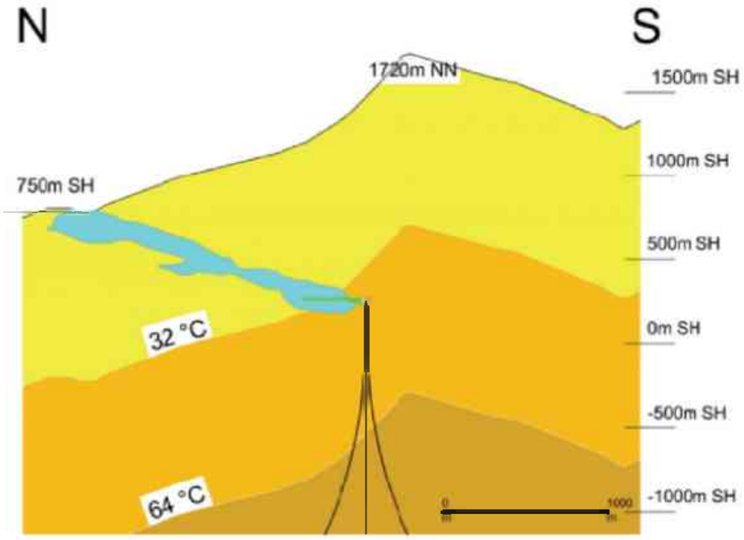


Figure 11: Temperature profile of the project region. (NN and SH are referring to the sea level).

The vertical difference between surface and well location is, therefore, 1,000m.

4.4 Required Cavern Space

Since the drilling rig will be located in a subsurface cavern, the dimensions of this cavern must be defined. The minimum measurements for length, width and height follow accordingly follow the dimensions of the selected drilling rig (4.2). To ensure a degree of freedom in the planning phase, length, width and height were respectively set to 40m, 30m and 45m.

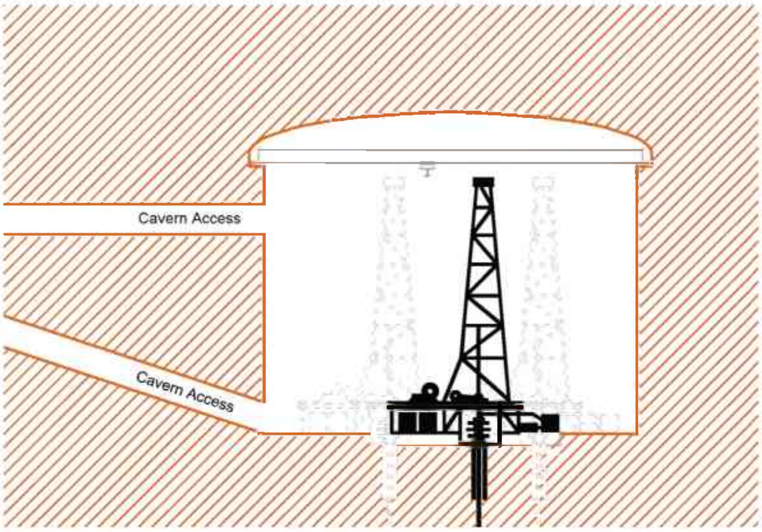


Figure 12: Schematic sketch of the subsurface cavern for the drilling rig accommodation (Chair of Subsurface Engineering, Montanuniversitaet Leoben, 2015)

Figure 12 shows a schematic sketch of a drilling rig in subsurface located in a cavern. It must be noted that the cavern must not be of cuboid shape. The full height of 45m must only be provided for a certain area where the derrick is located, and along a radius where the derrick is erected. Thus, the rest of the cavern can be significantly lower.

4.5 Access Road Inside the Mine

To guarantee the transportation of tools and machinery to the construction site in the cavern, the galleries and spiral galleries must feature sufficient measurements in height and width, and also radius, for the spiral gallery. The single components of the modular built drilling rigs are transported on conventional trucks and flatbed trucks. Thus, the dimensions of the largest transport unit are crucial for the successful realization of the equipment transport. Established transport contractors (Rachbauer, Felbermayr) offer heavy load trucks with lengths of up 40m and widths of up to 4m. The turning cycle of an standard three-axle truck is 19 – 20m (Daimler AG, 2016) and, therefore, much smaller than the inner and outer diameter of the spiral galleries in the mine. A trailer attached to the truck will increase the turning cycle, depending on the length of the trailer, whereas steered rear wheels of the trailer minimize the turning cycle again. Figure 13 and Figure 14 respectively show the elevation and plan view of the project mine. The entrance of the mine is located on the top left of the figures, the possible cavern location on the bottom right.

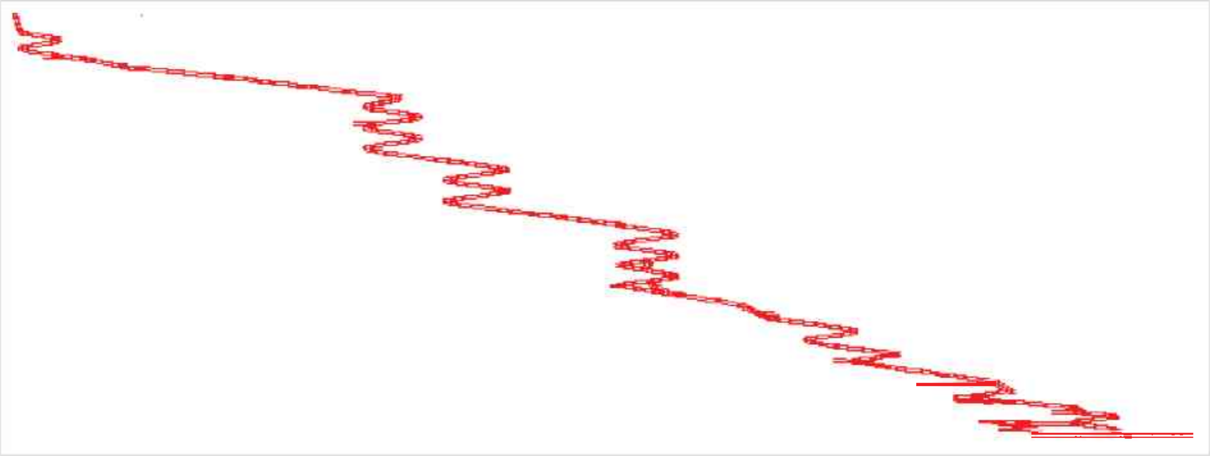


Figure 13: Elevation of project mine

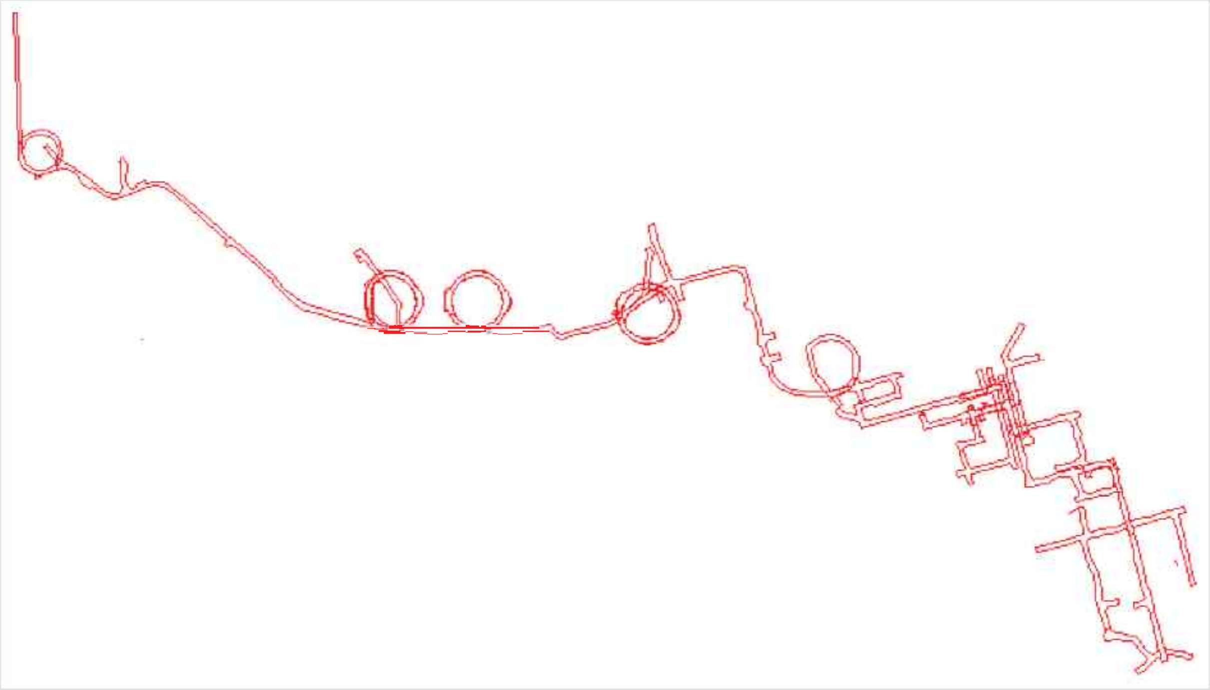


Figure 14: Plan of project mine

An analysis of the CAD plans of the project mine has resulted in 5.2–6.2m width, 3.5m height, inner radius of a spiral gallery of 30m and an outer radius of 35.75m; the total length of the gallery network is 2,900m. Wide parts of the gallery network are paved and very well developed. The roads inside the mine are inclined up to 12%.

The calculated total length of the gallery network of 2,900m is also the minimum length for the supply, electricity, and piping systems to connect the subsurface drilling rig with the surface facilities. This minimum length is based on the assumption that the lines are laid along existing galleries and no additional supply shafts are constructed. If the routing is carried out trough the ventilation shaft, the distance will be shorter. To ensure enough space for vehicles to reverse, a second access to the mine is recommended. Because of the already existing dense network of galleries at the target location for the construction site in the mine (see Figure 14, on the bottom right), such a realization of a turnaround is feasible.

Bauer TBA 300 Transport

The following information is extracted from Chapter 5 of the Bauer TBA 300 operations manual (Bauer Deep Drilling GmbH, 2013). The Bauer TBA 300 Deep Drilling Unit is a modern, modular drilling rig that comprises of 53 transport units in which it can be disassembled. The basis for the individual transport units is provided by 30x 40ft-, 16x 20ft-, 2x 10ft-, and 5x custom-made-containers. The biggest standard-container measures 12,192 x 2,438 x 2,896mm (L x B x H), while the biggest custom-made container, which is also the biggest overall transport unit, measures 12,400 x 2,960 x 2,950mm. The overall weight of all 53 transport units is 929,247 kg, whereof the heaviest single transport units weighs 49,100 kg.

The individual units must be transported with proper transport vehicles, e.g. flatbed trucks or conventional trucks. Such trucks will fit into the galleries of the project mine and are, therefore, suitable for purposes of transportation. Locking and safety devices must be available and used. Stacking up the transport units up on top of each other is not allowed.

Recommendations for load suspension device:

- Heavy-duty crane with sufficient working height and load capacity
- Forklift with sufficient stacking height and load

Suitable cranes for operation gallery network are more difficult to find, since there is less requirement for heavy-duty cranes combined with small dimensions. However, cranes are available in Central Europe.

Table 2 provides a brief summary of the determined maximum dimensions and weight of the Bauer TBA 300 transport units.

Length [m]	12.4
Width [m]	2.96
Height [m]	2.95
Weight [kg]	49,100

Table 2: Maximum dimensions and weight of transport units

A list of all 53 transport units and their measurements is provided in Appendix A.

Outside the mine, no obstacles are encountered. The mine has a proper accessibility to the highway nearby, although the road is curvy.

4.6 Construction Site

The construction site must provide a footprint of 1,200m^2 to be in compliance with the required cavern space (4.4). All components of the drilling rig must be allocated inside the construction site and there must be some additional free space to allow for storage of tools, machinery, pipes and space for maneuvering of equipment and machinery.

A schematic drawing of the Bauer TBA 300 is shown in Figure 15. The generators for electricity supply (Figure 15, No.7) and the diesel tank (Figure 15, No. 8) can be situated outside the cavern, or omitted, when the power is supplied via the local grid. In both cases, strong enough electrical power lines must be laid either along the access road to the cavern or via the ventilation shaft. Furthermore, the complete solid control system may be relocated to the surface (Figure 15, Nos. 3, 4, 5, 6). The transportation of the drilling mud must be accomplished through an additional piping system.

Further challenges in the design of the construction site are the use of recyclable materials and reduction of waste for the construction of roads and walkways (Wirtschaftsverband Erdöl- und Erdgasgewinnung e.V., 2006). These routes must always be illuminated. An escape and rescue route must be attainable from all points of the rig and well signposted. Moreover, every location on the rig must be easily accessible.

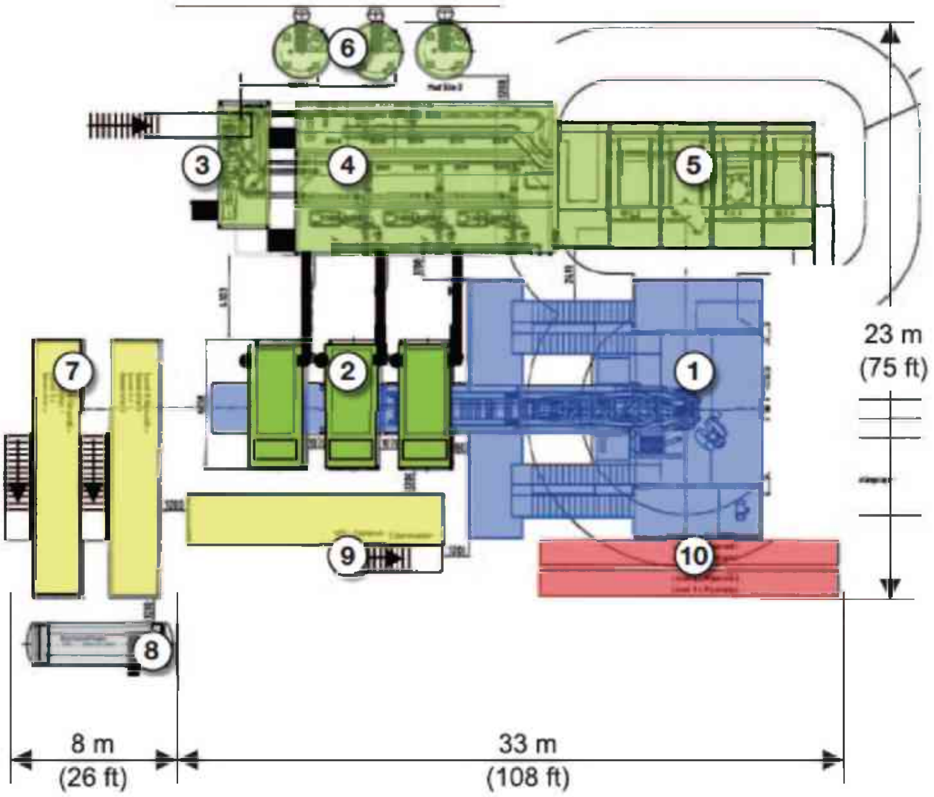


Figure 15: Schematic footprint Bauer TBA 300 Deep Drilling Unit, 33m x 23m footprint. 1 Derrick, 2 Mud pumps, 3 Mixing station, 4 Mud tanks, 5 Recycling unit, 6 Additional solids tanks, 7 Generators, 8 Diesel tank, 9 VFD unit, 10 Pipe handler (Bauer Maschinen GmbH, 2010).

For liquids, there are particular regulations. While drilling the well, lots of waste — in terms of liquid and solids — are generated. If it is not possible to separate and recycle the generated waste, this must be properly disposed of. The fluids must not enter the ground; hence, a sealed floor is mandatory.

With regard to water hazard, the construction site is divided into two areas:

1) Water hazard class area

Hazardous liquids must not enter the ground. This area includes the substructure of the rig, rig cellar, storage tanks for drilling mud, fuel deposits, shale shaker and every other area where hazardous fluids are handled. Special care must also be taken when dealing with drill pipes, casings and tubings.

2) Other areas

All other areas where no hazardous liquid is handled and no contamination of water can be expected are included in this class. These areas are — among others — thoroughfares, footprints for office, sanitary, repairing and assembling containers. Moreover, storage areas and the pipe handler also belong to this class.

4.7 Drilling Technology in Hard Formations

Drilling in hard formations is a great challenge for the profitability of the whole wellbore. Low rates of penetration, heavy wear of the drill bits and, thus, a high number of roundtrips are distinctive for hard formations. These parameters must be optimized in order to drill the well in an economical fashion. Solutions, therefore, are provided not only by the use of recently developed drill bits, but also by the use of innovative drilling technologies (Santos, Placido, & Oliveira, 2000).

Various factors influence the drilling process, like operating conditions, selection of the drill bit, type of geological formation, rock properties and type of drilling fluid.

From a broad variety of innovative technologies, most of which are still in the research and development phase and not ready for commercial use, two technologies are promising faster and more efficient drilling. The application of percussion air hammers and drilling fluid-powered percussion hammers are discussed in 4.7.3 and 4.7.4 respectively.

4.7.1 Laboratory Test for Rock Strength

In the oil and gas industry, the strength of a rock formation is only determined and classified only for the selection of the drill bit. The measured strength is assigned to one of five classes: soft, soft to medium, medium, medium to hard, hard. There is no standard classification that correlates the rock strength with the strength of the drill bit. One descriptive parameter for the assessment is the unconfined compressive strength (UCS). A rock is considered to be hard if the UCS exceeds a value of 10,000 psi (68.95 MPa) (Vieira, Lagrandeur, & Sheets, 2011). Chapter 3.2 discusses in detail the rock strengths of the geological formations in the project mine. Both rock formations can be considered as hard formations.

4.7.2 Selection of Drill Bits

Two entirely different types of drill bits are available for the selection of the drill bit.

The roller cone bit is usually made up of three cones, which are located around a circle and offset by a 120° angle each. Tungsten carbide inserts (TCI) mounted on the cone surface move along the rock surface and remove pieces of rock by chipping and crushing in hard formations and by gouging and scraping in soft formations.

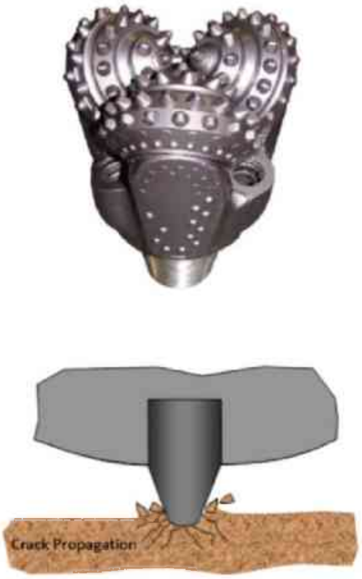


Figure 16: Roller cone bit (Ulterra, 2014)

Figure 17: PDC bit (Ulterra, 2014)

In contrast, the polycrystalline diamond compact (PDC) bit (Figure 17) removes chips of rock by shearing action. Less WOB is required for removing the same volume of rock from the formation compared to roller cone bits. In conclusion, it is better to choose a PDC bit for hard and abrasive formations, like in the project's formation. Roller cone bits (Figure 16) are also suitable for the use in hard formations, but their application is limited to a certain rock strength. Furthermore, PDCs are more efficient than roller cone bits. At a rock strength, as it is the case in the project's formation, the wear of the roller cone bit is disproportionate, and their operation is not economical. State-of-the-art values of UCS for rock that can be drilled efficiently are 45,000 psi for a 13mm cutter and 55,000 psi for a 8mm cutter (Fabian, 1994). These maximum values are greater than the measured values from the rock samples.

4.7.3 Percussion Air Hammer

The percussion air hammer technology is based on the functional principle of an air hammer that is located in the bottom hole assembly (BHA) behind the drill bit. Air streams inside the hollow drill pipe towards the hammer and actuates it into a reciprocating motion. The rock beneath the reciprocating drill bit is crushed by this vertical movement. The weakened rock can then be removed by the drill bit. The use of roller cone bits is preferred, since this type of bit is designed for crushing action. A big advantage of this system is the high rate of penetration (ROP) in hard formations with lower weight on bit (WOB) at the same time. Moreover, lower WOB and RPM are favorable for the lifetime of the equipment. Only dry gas, air with low water content, or foam, can be used as a drilling fluid. This is a clear disadvantage, since overbalanced drilling can not be applied. Further on, it can result especially in considerable disadvantages in exploration wells. The penetration rate in a 1,200m-thick, hard and abrasive conglomerate formation, with UCS values above 25,000 psi, in Oman, could be enhanced by the use of a percussion air hammer. The drilling time was reduced from 29 days to 5 days, the average ROP was increased to 45 m/h, in comparison to 1-2 m/h earlier with conventional drilling methods (Vieira, Lagrandeur, & Sheets, 2011).

4.7.4 Drilling Fluid-Powered Percussion Hammer

These percussion hammers can be operated by the used of conventional drilling fluids, in contrast to the air hammer. The same amount of WOB and energy can be transferred to the bit, as it would be the case without a percussion hammer. Figure 18 shows the functional principle. First, the valve is opened and the piston moves back from its striking position. The piston gets in position, ready to strike. The valve closes and the high-pressure water (up to 180 bar) forces the piston to strike. The piston strikes the bit. The valve opens to release the water through the bit. A new cycle starts. By the use of the high-pressure water stream, an overbalanced drilling operation can be achieved, and, the formation water therefore kept in the formation.

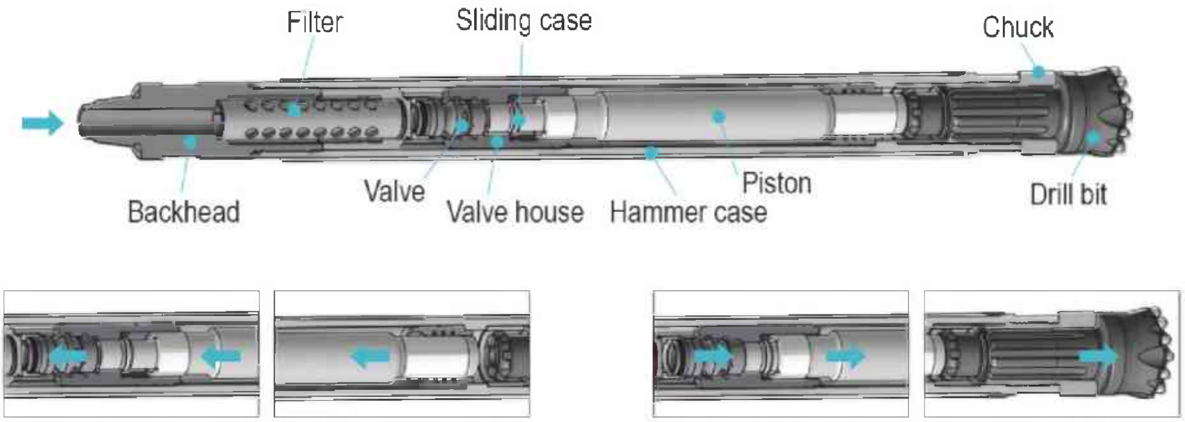


Figure 18: Functional principle of a drilling fluid-powered percussion hammer (LKAB Wassara, 2015)

The use of a drilling fluid-powered percussion hammer in the Severnaya Truba Field in Aktobe, Kazakhstan doubled the ROP in a 750 m thick formation to 6.9 m/h; the drilling time was, therefore, halved from 14 to 7 days (Powell & Hu, 2015).

The field tests with percussion air hammer and drilling fluid-powered percussion hammer prove the enormous potential that can be unlocked by the use of appropriate drilling technology. With the correct selection of drilling tools, especially bits, efficiency is increased, and the well can be drilled in a more economical way. However, an optimization is only possible if sufficient data about the geological formation is available. In the case of an exploration well, such applied technology will initially not show that much of an improvement, since information must be gathered first. Subsequent appraisal wells will ultimately benefit from the data gathered while drilling the exploration well.

5 Wellbore Design and Completion

The selection of casing grades and weights is affected by many factors like local geology, formation pressure, hole depth, formation temperature, logistics and various mechanical factors. This chapter provides a brief overview of the purpose of casings and discusses design criteria, especially with respect to geothermal usage and common loads acting on the casing from outside and inside.

5.1 Casing Program

Figure 19 shows a typical casing program which is used in the oil and gas industry. The principle idea is also applicable in geothermal wells, without any alterations of the program. The number of casing stings (e.g., surface, intermediate, production) depends on the depth of the well and on the prevailing pressure regime around the well, formation as well as mud pressure. Casing strings reach from the top of the well to the individual end of each string, whereas casing liner do not start at the top of the well. They are hung into a liner hanger, located at the end of the previous casing string or liner.

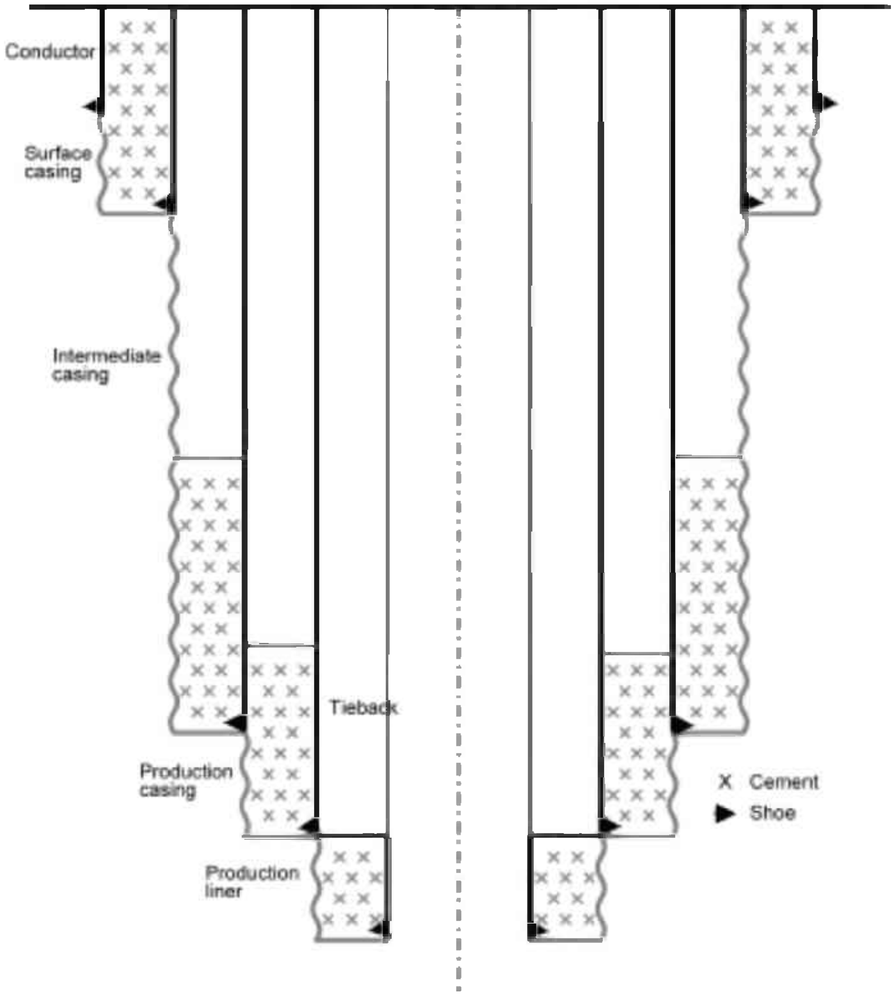


Figure 19: Typical casing program (Lake & Mitchell, 2006)

The annulus between the casing and the formation is at least cemented a couple of meters to ensure wellbore integrity. Chapter 5.8 provides a detailed discussion on cementation.

5.2 Purpose of Casing

A casing has similar purposes when drilling a geothermal well compared to an ordinary oil and gas well. Since the objective is to develop a deep geothermal probe, where a closed loop circulation is applied, and, therefore, injection and production of the circulating fluid occurs in the same wellbore, no interaction with the formation will take place. This reduces the tasks of the casing.

The main tasks of the casing are:

- Supporting the weight of the wellhead and BOP
- Providing circulation for the drilling mud
- Controlling well pressure by containing downhole pressure
- Isolating high pressure or permeable zones
- Isolating other trouble zones that may lead to problems while drilling
- Separating of different pressure of fluid regimes
- Providing stable environments for production equipment, e.g. packer, SSSV
- Avoiding fractures of formations while drilling next section with higher mud density

5.2.1 Conductor Casing

The conductor casing is the first casing string; its objective is primarily to ensure protection and stabilization of loose surface soils from erosion caused by the circulating drilling mud. A further purpose is the guidance of the drill string and subsequent casing strings into the hole. The verticality and centralization of the conductor casing is of great importance, since subsequent strings will deviate in accordance with the first string. Regarding corrosion aspects, the conductor serves as sacrificial protection for the inner casing strings. These inner strings are also protected from stresses, exerted by the movements of the drilling rig.

Usually, the conductor is driven down to the setting depth, which makes it necessary to design for hammering loads. Alternatively, the conductor can be run into a predrilled hole and cemented. This procedure is necessary in the construction of the project well due to hard rocks already present in the first few meters. Essentially, there is no loose soil. Although a conductor might not be required from the technical point of view, the Austrian law requires a conductor casing. Furthermore, there is a reduced risk for inrush of formation fluid when drilling the first few meters of the well instead of drilling only the longer surface casing section under the same conditions of possible high pore pressure.

5.2.2 Surface Casing

The aim behind installing a surface casing is to support poorly consolidated shallow formations against collapse, allow for drilling mud circulation and protect groundwater horizons from contamination caused by the ongoing drilling process. Moreover, there is also the possibility of shallow hydrocarbon accumulations that need to be sealed off by the casing. To ensure the fulfillment of these requirements, the surface casing is cemented the whole length up to the surface. While drilling, the blow out preventer (BOP) is mounted on top of the surface casing string. In addition, the wellhead and subsequent casing strings are supported by the surface casing as well.

5.2.3 Intermediate Casing

The main purpose for an intermediate casing string is to avoid drilling problems, e.g., to provide protection against blow-outs or to isolate over-pressured or permeable formations. An additional string may also be planned when the mud weight for drilling deeper sections exceeds the fracture resistance of shallower formations.

5.2.4 Production Casing

This is the last and innermost casing string in the completion design of the well. For oil and gas wells, the production casing serves — as indicated by its name — for production of the reservoir fluids. Since the objective here is to circulate media inside the wellbore, an interface between well and formation is not needed. However, if the target formation is impermeable, an open-hole completion can be very well suited.

5.2.5 Production Liner

Instead of — or subsequent to — a production casing a production liner may be installed. A liner is a casing string that does not extend all the way up to the surface. The liner is installed via a liner hanger a short distance above the casing shoe of the previous casing string. An overlap of 100m for a 7” liner between the previous casing string and the liner is recommended (Wirtschaftsverband Erdöl- und Erdgasgewinnung e.V., 2006).

The choice of a liner has numerous benefits:

- Reduces material costs
- Allows rigs with lower tensional load limitations (hook load) to drill for deep wells
- Has a larger production diameter (ID of previous casing string) above the liner hanger, which allows for better flow characteristics

Although liners are preferred from an economic viewpoint, the possible disadvantages must also be considered and taken into account in the design process:

- Risk of bad cementation job due to reduced clearances, especially in the liner hanger section
- Risk of cementing the liner running equipment in place
- Risk of poor pressure integrity due to bad cementation or extensive wear at the liner hanger
- Previous casing string must withstand the circulated media, since a direct contact between the casing and the fluid is given above the liner hanger

- The use of a liner makes it necessary for the previous casing string to withstand the pressures from lower depth

5.3 Selection of Casing Setting Depth and Casing Sizes

The determination of the casing setting depth is the first step in the casing design process. It is based on many factors, such as: total depth of well, pore pressure, formation breakdown pressure, problem zones, availability of casing, connectors and wellheads, and the economics.

The information required for the evaluation process is found in seismic and geologic evaluations of the drill site as well as from drilling data of nearby wells in the area. No detailed information is as yet available for the desired prospect area; so the process is based on only a few and rough data. The key to success in evaluating setting depths is to assess the prevailing pore pressure and formation breakdown pressure (fracture gradient) versus depth.

The selection of setting depth is based on a graphical approach. Starting from the bottom, a mud weight equal to the pore pressure plus safety margin is selected and projected vertically till it exceeds the fracture pressure minus safety margin. Continuing with a lower mud weight, selected at the depth where the fracture pressure has been exceeded, the process is repeated as many times till the surface is reached. The total number of mud weights used from bottom to top equals the amount of casing strings required.

The setting depth of the conductor casing is usually shallow, as its main objective is only to provide a structural basis for subsequent casing strings and allow for mud circulation. Therefore, the setting depth must be an impermeable and competent formation, with sufficient fracture resistance. The selected diameter must be large enough to accommodate the inner casing strings.

5.4 Casing Design

For the selection of the casing, a series of criteria has to be considered. Calculation is based on uniaxial load scenarios for each of the three casing strings. Burst, collapse and axial tension are considered for each casing string. There are inner and outer pressure profiles for the surface casing, intermediate casing and production liner, respectively. These pressure profiles represent the load acting on the inner side and on the other hand, on the outer side of the casing. As regards to the maximum hook load the rig can support, the casing must not exceed a certain weight. The axial tension on top of each casing string must not exceed the manufacturer rating for the strength of the pipe body and casing connectors. A balance between selected casing grade and weight per length is required in order to keep costs low. A better casing grade and higher weight per length result in higher costs. However, the discussed requirements discussed — may under no circumstances — be neglected to reduce costs.

The most important factor in designing casing for geothermal wells is the effect of temperature. Geothermal wells are generally classified as high temperature wells, since their objective is to reach depths of high heat content. It is mandatory to increase the resistance against high temperature by carefully selecting material grades, based on experience from oil and gas wells, and to increase the wall thickness of the pipe (Teodoriu & Falcone, 2008).

Temperature also influences also the quality of connections between two casing joints. Standard API LTC connectors have reportedly shown that they cannot withstand high compressional or tensional loads under high temperature influence. API Buttress connectors are way more suited for geothermal applications. The best choice would be casing drilling connections, as they are designed to withstand high axial loads and torque (Teodoriu & Falcone, 2008).

The assumptions for the calculation base represent the worst conditions that may act on the casing. These conditions may occur during drilling or during the operation of the geothermal well. The probabilities of the occurrence of such conditions are minor; nevertheless, the well must be designed in this way, since it is an exploration well. The basis for the design of the casing was the guidelines from Wirtschaftsverband Erdöl- und Erdgasgewinnung e.V. (2006).

5.5 Outside Pressure Profile

Only one outer pressure profile for all burst and collapse loads is necessary. Those of the hydrostatic liquid column, which is acting in the casing-tubing annulus over the whole wellbore length. TVD_n specifies the depth at which the pressure should be calculated.

$$p_a = \rho_{mud} \cdot 9.81 \cdot TVD_n$$

5.6 Inner Pressure Profile

The inner pressure profile is split up in scenarios for burst and collapse loads.

5.6.1 Burst Scenario

Burst loads — at a specific point — are derived from multiple superimposed burst load scenarios. For each section along the wellbore, different inside and outside pressure profiles do exist. To calculate the resulting burst load, the outside pressure profile must be subtracted from the inner pressure profile. Hence, the resulting force acts from the inside to the outside. Burst loads occur with high likelihood at the wellhead and at the liner hanger.

Maximum possible shut-in pressure

This load scenario applies only during drilling. A gas influx from the next section, which is currently drilled, is assumed. The complete wellbore is then filled with gas, which has a way lower density than the drilling mud. The resulting maximum wellhead pressure is calculated by subtracting the gas column in the wellbore from the fracture pressure of the formation at the casing shoe.

$$p_i = \rho_{frac} \cdot 9.81 \cdot TVD_{csg.\ shoe} - \rho_{gas} \cdot TVD_{csg.\ shoe}$$

The maximum possible shut-in pressure is used for the inner profile calculation.

Wellhead pressure is 40% of bottomhole pressure

This load scenario applies only during drilling. A trapped gas kick rises up to the wellhead due to buoyancy and stays above the dynamic liquid level of the wellbore. The pressure exerted from the gas column against the wellhead is assumed to be equal to 40% of the hydrostatic pressure of the underlying liquid column.

$$p_i = 0.4 \cdot \rho_{mud} \cdot 9.81 \cdot TVD_{bottomhole}$$

This load scenario is used for the evaluation of the inside pressure profile.

Full gas column

This occurs during drilling or during production. The wellbore is shut in and completely filled with gas, starting from the casing shoe up to the wellhead.

$$p_i = \rho_{formation} \cdot 9.81 \cdot TVD_{csg.\ shoe} - \rho_{gas} \cdot TVD_{csg.\ shoe}$$

The full gas column scenario is used for the calculation of the inner pressure profile.

5.6.2 Collapse Scenario

Similar to the burst scenario, the collapse scenario comprises of inside and outside pressure profiles. The inside profile is subtracted from the outside profile in order to get a force, acting from the outside on the inside.

Inside partially empty

This scenario may occur during drilling, when the drilling mud losses in highly permeable regions or even in thief zones appear. The height of the resulting liquid column results from the balance between the hydrostatic pressure of the liquid column and the formation pressure.

$$TVD_{mud} = TVD_{bottomhole} - \frac{\rho_{formation} \cdot 9.81 \cdot TVD_{bottomhole}}{\rho_{mud} \cdot 9.81}$$

$$p_i = p_{surface} + \rho_{mud} \cdot 9.81 \cdot (TVD_{csg.\ shoe} - TVD_{mud})$$

The load scenario inside, partially empty, is used to calculate of the inside pressure profile for the surface and intermediate casing section.

Inside empty

Occurs only during production due to unwanted evacuation of the tubing. The inside pressure then equals then the atmospheric pressure of 1 bar.

5.7 Yield Strength Reduction due to Temperature

Temperature affects the yield strength of materials; for burst and axial strengths, the reduction in yield strength is proportional to the temperature. The collapse yields strength is also dependent on the temperature, but to a lesser extent. For collapse, the D/t ratio of the pipe has a greater influence. API Bulletin 5C2 (American Petroleum Institute, 1999) provides the yield strength of common pipes used in the oil and gas industry. These values should be used as a starting point for the design process. In average low-grade materials, the yield strength is reduced by 0.081% per °C. Figure 20 shows the dependency of the yield strength from temperature. An bottomhole temperature of 180°C results in a yield strength of 87% of the original value. This linear calculation approach is — despite its conservativeness — not valid for all pipe grades and materials. Accurate estimations of the yield strength reductions are usually provided by the manufacturer of the pipe (BG Group, 2001).

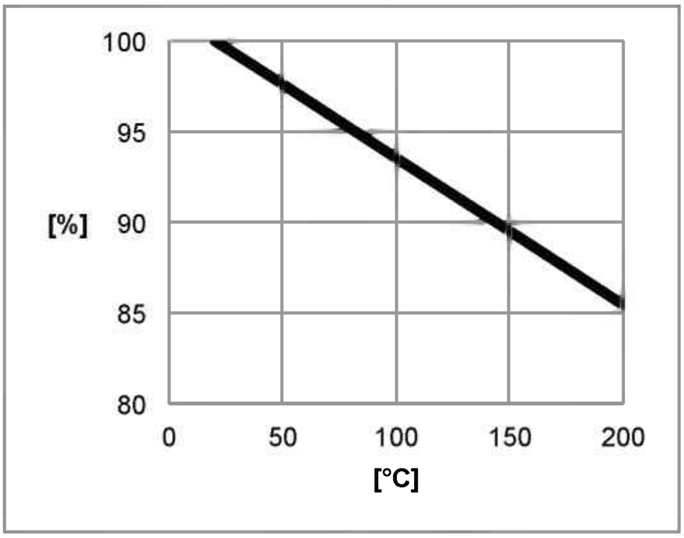


Figure 20: Yield strength temperature correction

5.8 Cementation

According to §32 (4) of the Bohrlochbergbau-Verordnung (Republik Österreich – Bundesminister für Arbeit und Wirtschaft, 2005), the Austrian law on the construction of deep wellbores, the cementation must anchor the casing with the formation and, furthermore, ensure a tight seal. Furthermore, §32 (5) requires a length of the cementation in order to preclude communication between different horizons along the borehole wall and also communication from those layers with the surface. Paragraph 32 summarizes the requirements for the cementation, which are:

- Zonal isolation
- Anchor and support casing
- Protect casing against corrosion from formation fluids
- Support wellbore walls in case of weak and unconsolidated formations

A cross-sectional view across formation, cement, casing and tubing is shown in Figure 21.

Figure 21: Cross-section formation — wellbore. From left to right: formation (brown, dotted), cement (gray — dotted part represents cement penetrated into formation), casing (black), cold water stream downwards (blue), tubing (black) and warm water stream upwards (orange).

It is common practice to cement geothermal wells over the entire length up to the top. This is due to several reasons. First, the cementation avoids, or, at least, limits the expansion of the pipe material to a certain degree. Elongation of the pipe is restricted, which can be of advantage if no constant flow is present in the system. The pipe will be subject to cyclic elongation and contraction. Buckling of the casing is also prevented, since the casing is fixed to the formation, and has no possibility to move. As a last remark, cement can have very good thermal conductivity if a cement tailored for geothermal applications is used. Without cement, there may be air between the casing and the formation. Air acts like an insulator for heat transfer, which, in turn, reduces the efficiency of the system.

5.9 Tubing Design

The tubing is a concentric pipe, the geometry of which basically is defined by its OD and ID. The OD of the tubing is smaller than the ID from the innermost casing string in a well, so that it can fit inside it. The annulus between casing and tubing created, therefore, serves as an injection path for the circulated fluid in a geothermal application. The circulation fluid, most likely fresh water, with a temperature T1, is pressurized on surface and pumped down the annulus. When moving down the annulus due to injection pressure and gravitation, the water is heated up through the increasing geothermal gradient. When reaching the bottom of the wellbore, the water temperature has increased to T2. The fluid then streams inside the tubing and upwards. By the use of proper insulation, the temperature of the fluid should be kept constant over its way back to the surface. Heat losses must be reduced to a minimum for ensuring an optimum overall efficiency of the system.

Insulation can be achieved by the use of several different concepts:

- Re-lined tubing — stainless steel pipes that are coated on the inside with heat-insulating plastic
- GRP — glass fiber reinforced plastic
- Double-tube with vacuum insulation

As far as the expected loads are concerned, load conditions must be considered. As for the casing, burst, collapse and axial tension are taken into account. The API has released the corresponding guidelines 5CT for the selection of the tubing. For the use of tubings in geothermal applications, a temperature dependency of the steel must also be considered, as well as a proper insulation of the material.

6 Environment Analysis

A major part in the evaluation of a subsurface operating drilling rig are HSE considerations. Factors that are critical for the success of the project are organized in thematic groups, their impact on various operations or the overall project is assessed, and ultimately measures for avoidance, or — if it is not possible to avoid these — measures for mitigation are defined.

6.1 Transport

One of the most critical aspects of the operation of a drilling rig is transportation. The individual parts must be in time on location in time. Space is often limited, more than ever in a restricted cavern. Thus, careful planning in two domains is critical. First, the dimensions of the transported object must be evident. Secondly, a proper time management must be set up. Table 3 lists influencing factors in relation to transportation issues. Moreover, a mutual interference between the drilling operation with its overall supply needs through the mine and the operation of the mine itself must be avoided.

Influencing factor	Risk	Measure
Transport of personnel to and from the wellsite	Work progress is delayed, or may even come to a standstill	Set up detailed timetables, introduce a stand-by duty
Transport of personnel in case of an emergency	Health hazards, even lethal consequences	Evacuation and emergency plan must be set up in advance
Transport of material and machinery to and from the wellsite	Work progress is delayed, or may even come to a standstill	Detailed planning in the preliminary stage of operation with respect to dimensions; coordinate on-time supply of goods; determine decomposability of tools and machinery
Energy (electricity)	Work progress is delayed, or may even come to a standstill; safety issue	Installation of a two-way power supply, high voltage current line over grid, plus emergency generator on site
Energy (diesel)	Work progress is delayed, or may even come to a standstill; safety issue	Store an emergency amount near the cavern, properly secured; use electrical drives wherever possible; refueling of vehicles outside of mine
Cuttings	Need to be removed from mud treatment facility, otherwise system may get blocked	Disposal in nearby galleries, or transportation to surface via pipe or belt conveyor

Table 3: Environmental analysis, transport

6.2 Shortage of Space

The subsurface cavern is limited in space. Access roads to — and from — the cavern are constructed in a way that freedom of movement is possible. Considerations about the space for storage areas, rigsite, accessibility of the rigsite and maneuverability of trucks, cranes and other vehicles must be made. The aspects considered are listed in Table 4.

Influencing factor	Risk	Measure
Transport of personnel, equipment and material to and from the wellsite	Work progress is delayed, or may even come to a standstill	Set up detailed timetables, account for uncertainties; know all dimensions of the equipment beforehand
Sufficient space for operating the machines and vehicles	Work progress is delayed, or may even come to a standstill	Detailed planning in the preliminary stage of operation
Storage space for material, containers, vehicles, pipe handler for casing and tubing	Work progress is delayed, or may even come to a standstill	Detailed planning in the preliminary stage of operation
Storage space for additional drilling mud and additives	Excessive fluid loss may empty the tanks and endanger the drilling process	Detailed planning in the preliminary stage of operation

Table 4: Environmental analysis, shortage of space

6.3 Mud Losses While Drilling

One of the greatest fears of a drilling crew is to encounter significant drilling mud losses while drilling. A loss can be due to various reasons and is, therefore, difficult to predict in advance (Table 5).

Influencing factor	Risk	Measure
Losses due to faults, fracture networks, karstification, caves or other reasons	Loss of significant amounts of drilling mud into the formation: drilling must ultimately be stopped; abandonment of borehole	Gathering and analysis of various geological and geomechanical data in order to detect thief zones; design of a sound mud system plus contingencies

Table 5: Environmental analysis, mud losses while drilling

6.4 Occupational Safety

Considerations for occupational safety are generally valid in any working environment: in the construction industry, in particular, where operating heavy machinery is a daily routine, movement of heavy loads and exposure to all kind of emissions are common. Influencing factors, risks and measures for occupational safety are shown in Table 6.

Influencing factor	Risk	Measure
PPE (Personal protective equipment)	Workers are not wearing equipment or are wearing faulty equipment	Ensuring the absolute necessity of wearing PPE in accordance with the executed task; functionality of equipment must be checked
Explosion hazard area	Danger of explosion	Use of only Ex protected devices; scrutiny devices on a regular basis
Handling of chemicals	Health hazard, even lethal consequences	Training for the handling of particular chemicals; special safety equipment for certain activities
Dust	Impairment of vision; long exposure time causes breathing problems	Prevent dust formation; use ventilation systems; dust removal by suction
Sparks, welding work	Danger of explosion; ignition of certain materials, fire	Welding work only in prepared areas; storage of explosive and flammable materials in safe custody
Fire	Danger of explosion; ignition of certain materials	Store flammable substances and materials separately; reduce ignition sources to a minimum and avoid wherever possible; evacuation plan
Optical radiation, laser	Impairment of vision	Wearing of protective glasses; performance of work only with required personnel on site
Gas	Health hazards, even lethal consequences	Gas detection and warning system; respiratory protection; evacuation plan
Working at heights	Fall; danger of severe injury	Fall protection
Failure of light system	Danger of accidents	Emergency generator; emergency light; flashlight
Failure of ventilation system	Danger of suffocation	Emergency ventilation system; filtering devices; respirator
Collapse of the cavern	Danger of severe injury; damage of entire gear	Use only Ex protected devices; carry out scrutiny of devices on a regular basis

Table 6: Environmental analysis, occupational safety

6.5 Noise Pollution

A big advantage of subsurface drilling is the nonexistent impact of noise targeting residents. The only affected group is the drilling crew and other workers present near the drilling rig. However, the noise level must be kept within the limits enlisted in the working conditions act. Aspects related to noise pollution are shown in Table 7.

Influencing factor	Risk	Measure
Exposure to noise pollution for residents	Not-existent	No measures must be taken
Compliance with the maximum allowable concentration for noise pollution	Health hazards; permanent long-time damage of hearing	Use of noise prohibiting devices, such as hearing protection; low-noise machinery and vehicles; noise barriers for extremely loud areas

Table 7: Environmental analysis, noise pollution

6.6 Interference due to the Parallel Ongoing Mining Operation

Activities that occur during the regular operation of the mine might interfere with the drilling operations in the cavern. Influencing factors therefore are listed in Table 8.

Influencing factor	Risk	Measure
Fire in the mine	Endanger the drilling operation; cut-off supply for the rig and transportation routes	Install automatic fire barriers at the mine entrances; Set up fire compartments; evacuation plan
Blasting vibrations	Interference of the drilling operation; disturbance of rig sensors	Record vibrations in advance of the drilling operation and analyze possible influence; Pause drilling operation while blasting is ongoing
Blocked access road to the cavern, e.g. stuck truck	Shortage of rig supply; blockage of emergency route	Storage of vital goods in cavern to survive a certain timespan; emergency tools

Table 8: Environmental analysis, interference due to the parallel ongoing mining operation.

Information about the requirements of an evacuation plan and the general access to a mine can be found in the Austrian regulation AStV (“Arbeitsstättenverordnung”), §18 “Abmessung von Fluchtwegen und Notausgängen” as well as in the “Allgemeine Bergpolizeiverordnung”, Chapter VII. “Fahrung”, §96 – §113.

6.7 Inflow of Gas or Water from the Formation

Despite accumulations of gas, an that aquifers are not expected in the project are, an inflow of such fluids must always be taken into account (Table 9).

Influencing factor	Risk	Measure
Unexpected inflow of gas- or water-bearing layers during drilling	Complications during drilling; endangerment of workers safety; blow out may occur	Proactive monitoring of real-time drilling data, early detection of fluid bearing layers; additional catch tanks for fluids; use of closed circulation system by default

Table 9: Environmental analysis, inflow of gas or water from the formation

6.8 Number of Employees in the Cavern

For the dimensioning of rescue and safety equipment it is necessary to give a declare a maximum number of employees that are present at the same point in time in the cavern. RAG Energy Drilling defines the amount of employees in a drilling crew: a drilling supervisor, a driller, an assistant driller, a derrickman, roughnecks, a mud engineer, a rig electrician and a rig mechanic (RAG Rohöl-Aufsuchungs Aktiengesellschaft, 2015). Therefore, a minimum of eight people must be present. During crew change, the amount of people doubles, since both crews are present at the same time. Along with additional employees from service companies or truck drivers, there are about 25 people present at peak hours.

6.9 Mine Ventilation

The supply of fresh air for persons and machines is vital. Further tasks of the mine ventilation systems are the dilution of harmful gases and cooling of the working areas, especially inside of the cavern. According to the Austrian regulation “Allgemeine Bergpolizeiverordnung”, Chapter XII. “Bewetterung”, §197 (4), a minimum required ventilation of $2m^3$/min per person is required. Furthermore, §197 (5) requires a ventilation of at least $6m^3$/min per horsepower for diesel engines. In the underground, there is always the possibility of occurrence of poisonous and explosive gases. These gases must be aspirated on a permanent basis to ensure the safety of all present employees. Governing factors for the climate in the mine are temperature, humidity, air velocity and air pressure. An evaluation of the climate is complex, despite the amount of measurable parameters. The dimensioning of the ventilation system is based on the governing factors.

The vehicles used in underground mining are equipped with a highly efficient waste gas purification system. Hence, a danger based on the use of combustion engines in the mine is negligible. The exhaust gas coming from the standard trucks, which are delivering the drilling rig and supplies, can be filtered with the mine’s ventilation system.

7 Workover of Geothermal Wells

Proper maintenance and operation are the key to success for extending the lifetime of geothermal wells. The oldest high-temperature well in Iceland has attained 47 years of age, according to Thorhallsson (2003). Many other wells are now 20 years of age or older. As a general rule, it is extremely important to design a proper initial construction of the well, the materials used should be state-of-the-art and appropriate for the prevailing pressure, temperature and chemical conditions. A sound cementation of the full length of the casing is very important.

7.1 Well Monitoring

Well monitoring is vital for the successful operation of a geothermal well in order to attain its objectives. The main purpose is to monitor the amounts of produced and injected fluids and to detect physical and chemical changes within the system. By monitoring the amounts of fluids, the expected energy output can be predicted, as also possible leaks in the casing or any other abnormality. For geothermal probes, it is common to continuously monitor wellhead pressure and temperature, total flow rate and performance properties of the pump near the wellhead. A permanent corrosion monitoring is conducted by installing corrosion coupons at the wellhead. In addition, caliper logs to check for scalings may be performed. Electronic devices are commonly used for measurements, since they are very reliable. However, a manual recording is still recommended to confirm the logged readings because of sensor problems, which may still exist in the harsh environment of geothermal wells. These problems may arise due to a two-phase flow, scaling along the pipes and valves, pressure pulsation and vibration (Thorhallsson, Geothermal well operation and maintenance, 2003). Usually, any changes in properties occur gradually, and reach a significant magnitude only after months or years after the initial occurrence. Thus, sudden changes in readings of measurements are related to the failure of measurement devices. A proper monitoring of the well's conditions can assist in predicting and planning of workovers or wellbore interventions.

7.2 Wellhead Maintenance

The wellhead may be the most affected part of a geothermal wellbore, since the only moving parts are located there. Visual inspections should take place every week in order to detect leaks or other damages. All welds must be checked before the well is put into operation, flanges and tool joints need proper bolting and reasonable torque must be applied. Valves are the most critical on their stems and seals. When an expansion spool is used in the wellhead, the packer must be maintained on a regular basis to ensure a pressure tight seal. The wellhead may be replaced after 20 years of operation, because of extensive wear and corrosion. Corrosion may also require to replacement of the first few meters of casing (Thorhallsson, Geothermal well operation and maintenance, 2003).

7.3 Casing Leaks and Failures

As fas as the casing in a geothermal well is concerned, leaks are the most serious and expensive problems that can arise. Several reasons can be responsible for such a casing leak: wear from drill pipes, thermal expansion and contraction, corrosion, bad welding, connector failure or bad cementing behind the casing. The most common reason is escaping steam from the annulus between two casing strings. Initially, the leak will be small, but it will grow steadily as the amount of penetrating steam increases and pathways expand. While casing fatigue is, in the meantime, fairly understood, cement fatigue remains less researched (Teodoriu & Falcone, 2008). According to Thorhallsson (2003), corrosion is not that big issue in geothermal wells. It is only near the surface that installations and pipes are prone to corrosion since the environment is moist and oxygen is present. The best corrosion protection is to keep the well continuously in operation; thus, no thermal stresses are induced, and oxygen has no chance to get into the wellbore.

Tubular fatigue may not only be the result of classic failures like overloading, corrosion or wear (Teodoriu C. , 2015):

- Fatigue can be induced while running the casing. Casing running should be performed as fast as possible to save rig time. At each joint, the running procedure must come to a standstill to connect the next casing joint. This ongoing go-stop cycles induce fatigue in the casing string; the maximum load is highest at the last connection.
- Vibrations that result during drilling in hard formations may cause drilling-induced fatigue. The harder the formation and the lower the ROP, the contact time between drill string and casing will be high.
- During workover operations and wellbore surveys, the well is subject to temperature variation-induced fatigue. Owing to changing temperature conditions, the casing will expand or contract in all directions.

7.4 Applied Workover Methods

The formation of scalings is the most common issue for geothermal wells, as indicated by Thorhallsson (2003). Types of occurring scales are calcite, sulphates and sulphides, which are dependent on the chemistry of each individual well. However, scaling is only an issue in hydrothermal wells where an aquifer is present, or in EGS wells, where the circulated fluid is in direct contact with the formation. This project well is executed as a single wellbore with a closed circulation system; hence, there is no influence from local formation or fluid chemistry. By using a proper working fluid together with inhibitors, scaling should not occur during the normal operation of the geothermal well.

Nevertheless, if there are any scales, they can be removed by several techniques:

- Applying a scrapping unit to the well, by using a trailer mounted drilling rig, workover rig or conventional rig. The casing is stressed due to the use of a cold workover fluid.

- Acid cleaning for calcite scales. Corrosion inhibitors need to be used because of the corrosive behavior of the acid.
- High-pressure jetting with coiled tubing units and water.
- Injection of a scale inhibitor at the wellhead or via a chemical injection line.

In conclusion, the need for workovers in geothermal wells is very limited, as historical data shows. To ensure trouble-free operations, some prerequisites must be met. The well should never be shut-in; circulation should take place continuously with a steady load, in order to preclude thermal stresses. Monitoring of the well is a must, so that leaks and other abnormalities are detected and repaired early enough. The cellar must be as dry as possible to avoid corrosion of the uppermost casing joints. Since the well will be naturally flowing with flow rates around $5m^3/h$ (RAG Rohöl-Aufsuchungs Aktiengesellschaft, 2013) and, therefore, no downhole pump is required, expensive pump changes will not occur.

Workover Unit

Despite the need for a workover is low, the Central European market for workover units was researched in order to find a useable unit. The Koller Workover & Drilling GmbH offers a broad range of mobile workover units, ranging from 34 to 62tons of applicable hookload (Koller Workover & Drilling GmbH, 2016). The required hookload capacity depends on the type of workover job that should be executed, e.g., casing replacement, change of tubing. All units are mounted on either a three or four axle truck. The height of the erected mast ranges from 21.5 to 29m, depending on the chosen size (hookload) of the workover rig. With a length of the truck up to 17.89m and a width of 2.75m, the truck will fit in the access road to the cavern. The crucial factor is the height of all available workover units, which measure 4m in height and, therefore, exceed the height of the mine galleries by 0.5m. Additionally, the working depth of the mentioned workover units is limited to 2,500m. Even the most recent mobile workover unit, a 90 tons five-axle truck (Koller Maschinen- und Anlagenbau GmbH, 2016), can not provide the necessary working depth of the project well.

The only feasible option for workovers are, although expensive and time consuming, stationary drilling rigs that are used for workover jobs. The company ITAG offers a wide range from small to medium drilling rigs that can be utilized instead of mobile workover units (ITAG, 2015).

8 Case Study

For later economic calculations a detailed wellbore design is required. The amount of casings strings, their setting depth, outside and inside diameter of casing and tubing, required mud volume, volume of thermal cement are factors that highly influence the overall costs of a wellbore. Along with the time it takes to drill the well, the completion demands a great portion of the costs. This chapter discusses the selected casings and their properties.

8.1 5,000m Subsurface Wellbore (Target TVD: 6,000m)

This case represents a vertical wellbore that targets a bottomhole depth of 6,000m. The drilling rig is located in a cavern 1,000m below the surface and, so, the remaining length of the wellbore to reach the desired depth is 5,000m.

8.1.1 Setting Depth, Casing Size Selection

The setting depths or installation depths of the individual casing strings are determined by the mud weight window. The mud weight window represents pore pressure, mud density and fracture pressure of the rock on the abscissa, whereas the depth is depicted on the ordinate. Because of the rarely available data, especially geological data, an assumption has to be made. For the rock density, the measured density of Amphibolite with 2,900 kg/m^3 was taken. A worst case is assumed for the pore pressure. The pores are assumed to be fully saturated with fresh water at a density of 1,000 kg/m^3. This is at once the heaviest possible natural fluid, if is zero salinity is present. The assumptions represent thereby represent a completely homogeneous geology from top to bottom. Figure 22 shows the dependency of pore pressure, fracture pressure and lithostatic pressure from depth. It is assumed that the pressure increases rapidly from ambient pressure to hydrostatic pressure at 1,000m depth within a few meters. An exact pressure curve can not be described, but must be determined through tests.

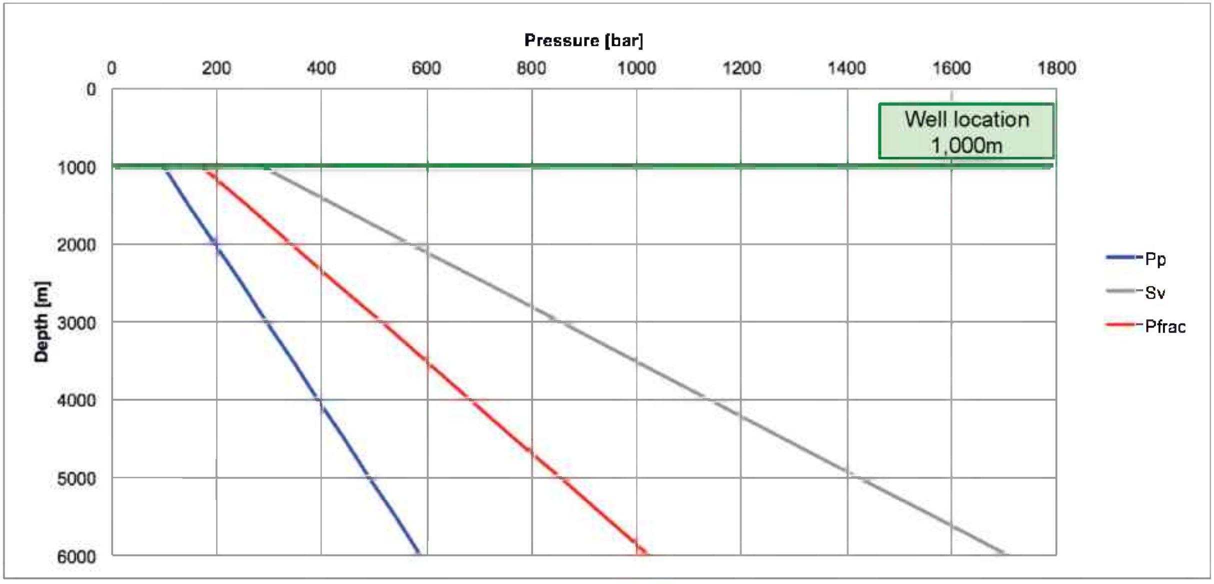


Figure 22: Pressure vs. depth curves for pore pressure (Pp), fracture pressure (Pfrac) and lithostatic pressure of the formation (Sv).

Three percent safety is included for the generation of the mud weight window, since there might be density variations in the drilling mud during operations. By applying the procedure explained in 5.3, the mud weight window is drawn, and setting depths are read from it.

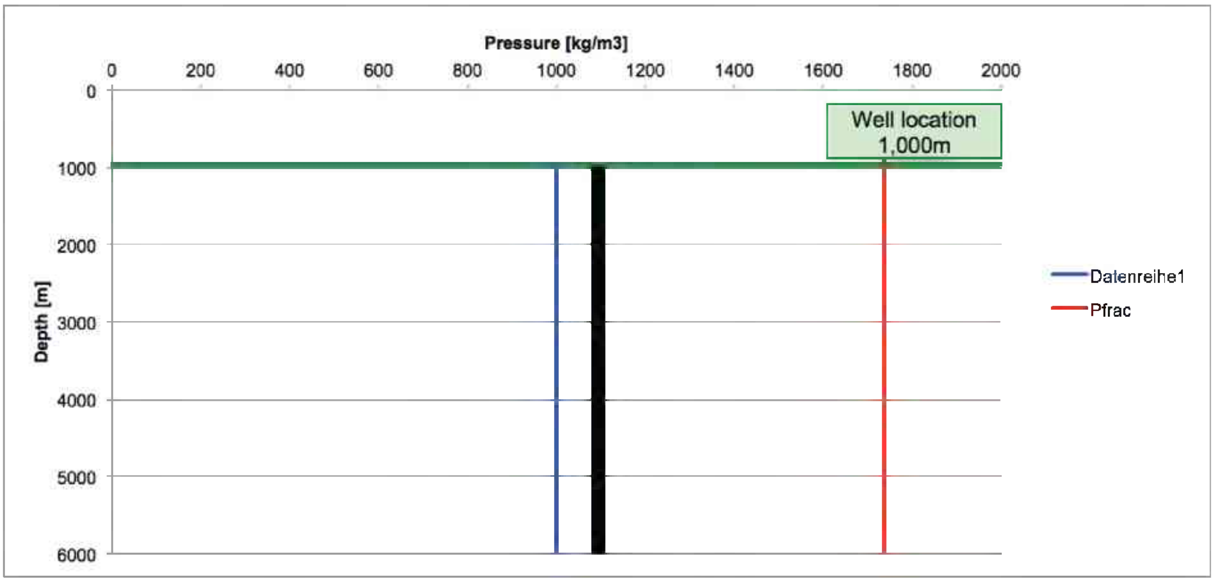


Figure 23: Mud weight window. Two straight lines for the pore pressure line and the fracture pressure line result as the consequence of a homogeneous lithology and density. The black line represents the mud weight required for drilling.

From the mud weight window (Figure 23), it is obvious that theoretically only one casing string is required for the whole wellbore, since the Austrian law requires a surface casing; additionally, because of contingency reasons, three casing strings are installed. If formations different than expected are found during drilling, there is a possibility to engineer another solution. Ultimately, this approach adds some margin to the design. The outside diameter of the production casing is set to 7” (Bauer, Freeden, Jacobi, & Neu, 2014). In around 70% of geothermal wells, the final diameter is 7” (Teodoriu C. , 2015). The diameters are denoted in inches, as defined by API specifications (American Petroleum Institute, 1999). Further casing diameters are determined with the aid of a casing and bit selection chart (Figure 24). Basically, there are two possibilities for the clearance between the inside diameter of the outer casing and the outside diameter of the inner casing — standard and low-clearance. The low-clearance scenario might be more cost-efficient, since smaller diameters — and, therefore, cheaper casings — can be used. But for the scope of this project with its exploration well status, a standard clearance is more favorable. An eventually needed additional casing string can be added to the design during drilling without reducing the original production diameter. The surface casing lasts until a depth of 300m below the well location (250m SL and 1,250m below surface). It serves as stabilization for the formation during the first few meters drilled. The intermediate casing is set inside the surface casing and reaches a depth of 2,600m. The innermost casing string, which is the production liner, is set at 5,000m and has a length of 2,500m. The superimposed length of 100m is required to install the production liner via a liner hanger in the intermediate casing.

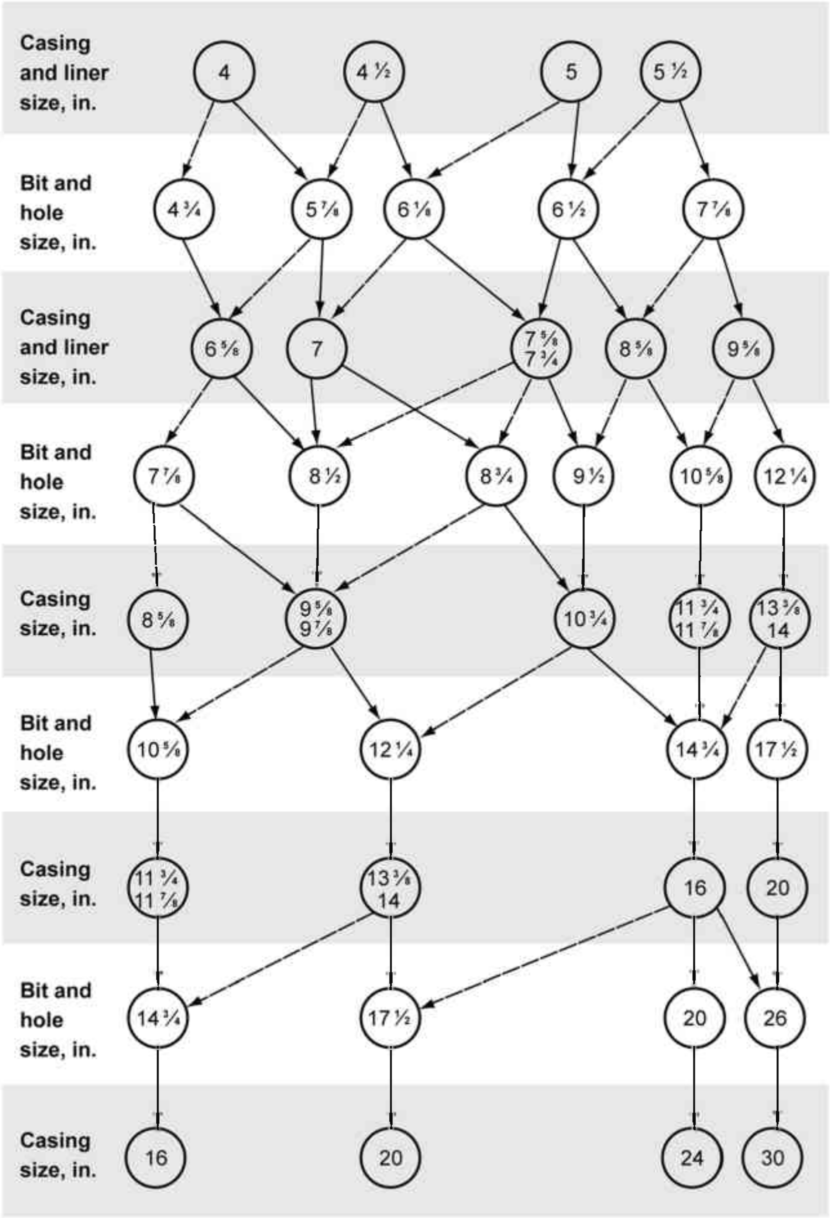


Figure 24: Casing and bit selection chart (Lake & Mitchell, 2006)

Table 10 shows the setting depth, length and OD for each casing string. Independent of these casing strings, a conductor casing must be installed. The purpose of this casing is the stabilization of the formation at the initial starting point of drilling. The formation in this area is already weakened by the construction of the cavern. The length of the conductor casing is assumed with 60m.

A special difficulty for the drilling process may be the prevailing pressure regime near the cavern. The pressure close to the ground surface in the cavern will be near zero, but increases rapidly. It may not be possible to drill overbalanced if the pressure is only provided by the drilling mud. A theoretical pore pressure of 98.1 bar is possible as the drilling starting point is 1,000m below surface. This problem can be overcome by using a drilling fluid power percussion hammer (4.7.4). The tool from the manufacturer LKAB Wassara (2015) is capable of providing a pressure of 180 bar in the very first few meters of drilling. Since no BOP is installed while drilling the first section, there needs to be a solution for regulated backflow of the drilling fluid. The drilling fluid is pumped down to the drill bit via a high-pressure pump and then leaves the nozzles towards the formation. In case of a tight formation, the fluid flows back through the annulus between BHA/drill string and formation. To collect the drilling fluid and return it into the flow system, a containment out of concrete around the top of the well, as a type of borehole cellar, will gather the drilling fluid. The fluid then must to be pumped back to the flow system. This solution does not allow for the application of back pressure to the well. Settling of cuttings in the concrete containment must also be avoided.

	OD	from	to	Length	
	[in]	[m]	[m]	[m}	[ft]
Surface Casing	13 3/8	1000	1300	300	984
Intermediate Casing	9 5/8	1000	3600	2600	8528
Production Liner	7	3500	6000	2500	8200

Table 10: Casing setting depth and OD for 7" production liner

8.1.2 Selection of Casing

Casing selection was done with guidance of API Bulletin 5C2 (American Petroleum Institute, 1999). This document contains information about the geometry and material strength for all important load cases for standard casings. Table 11 summarizes casing grade, OD, ID and weight per length for each section. Schematics of both designs are shown in Figure 25.

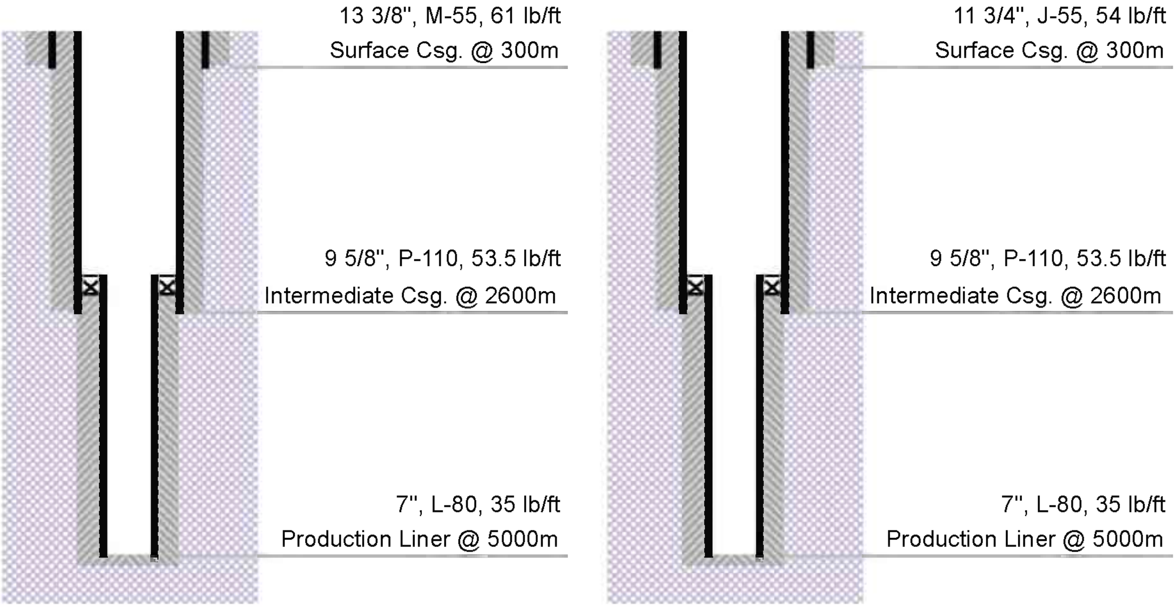


Figure 25: Casing Design 5,000m — Case A (left) and Case B (right), reference level for depths is from subsurface

A detailed walkthrough for casing design can be found in Appendix B for standard-clearance (Case A in Table 11) and low-clearance (Case B in Table 11). The low-clearance option offers to use smaller-diameter casings and, therefore, savings in costs compared to the standard-clearance option. An advantage of the standard-clearance option is that an additional casing string can be added to the casing program after the start of the drilling campaign, if unforeseen changes in the pressure regime occur.

	Section	Grade	OD	Weight per length	ID
			[in]	[lb/ft]	[in]
Case A	Surface Casing	J-55	13 3/8	61	12.415
	Intermediate Casing	S-95	9 5/8	53.5	8.535
	Production Liner	L-80	7	35	6.004
Case B	Surface Casing	J-55	11 3/4	54	11.000
	Intermediate Casing	S-95	9 5/8	53.5	8.535
	Production Liner	L-80	7	35	6.004

Table 11: Selected casings for Cases A and B

8.2 2,000m Subsurface Wellbore (Target TVD: 3,000m)

A different approach — in contrast to the single vertical wellbore, with a total depth of 6,000m — is to drill multiple (at least more than one) wellbores from one mutual cavern. Because of the fact that a 5,000m wellbore is associated with high costs, combined with the low geothermal energy recovery by a deep geothermal probe, the project will not be economically feasible in the first instance. The idea behind this approach is to get a higher energy output from shallower, but bigger, production diameter wells. The efficiency of such multi-well systems is subject to further research. The target depth for this scenario is 3,000m below surface; hence, a 2,000m-deep wellbore was designed.

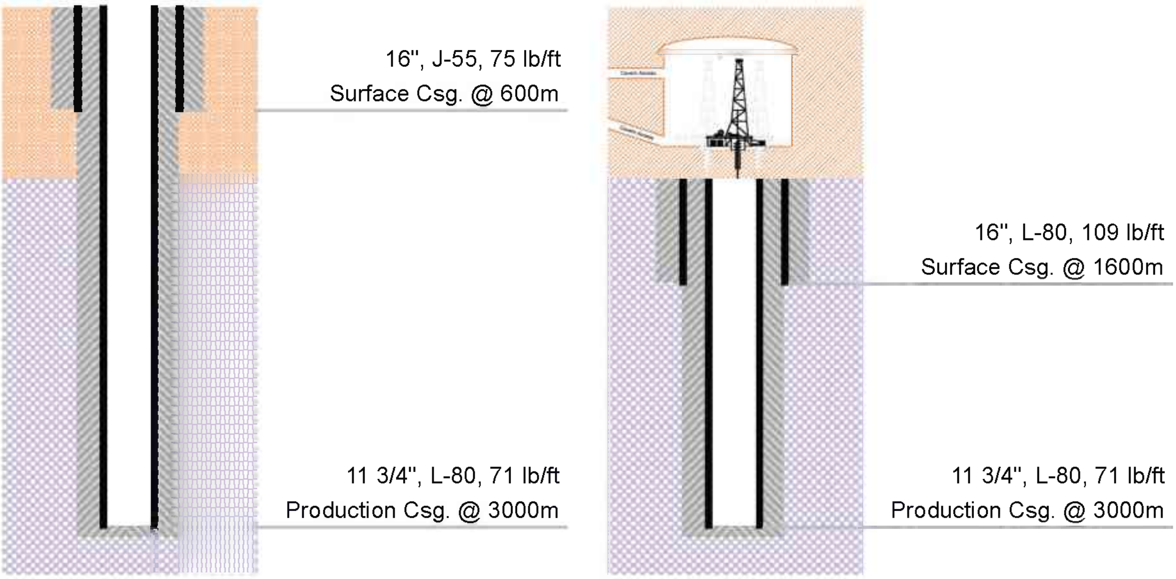


Figure 26: Casing Design TD 3,000m — surface (left) and subsurface (right), reference level for depths is surface

The outer diameter of the production casing was determined with the same principles, as discussed in chapter 8.1, and is 11 3/4". The setting depth of the surface casing is at 600m;

the final depth of the production casing is at 2,000m below the subsurface well location. A corresponding 3,000m wellbore for an economic evaluation was accordingly designed. Table 12 and Table 13 compares the designed wellbores for a target depth of 3,000m. Figure 26 shows the respective wellbore schematics. To perform an economic evaluation, the 2,000m wellbore is compared to a 3,000m wellbore, which is drilled from the surface. The wellbore has the same diameters for surface and production casing, in order to ensure equal heat extraction in both wellbores from the formation. The setting depth for the surface casing is 600m; those of the production casing 3,000m below surface.

	2,000m wellbore, subsurface						
Section	Setting depth [m]	Section length [m]	OD [inch]	ID [inch]	Casing weight/foot [lb/ft]	Cuttings [m^3]	Cement [m^3]
Bit size	-	-	20	-	-	-	-
Surface Casing	1,600	600	16	14.688	109	121.6	87.5
Bit size	-	-	14 3/4	-	-	-	-
Production casing	3,000	2,000	11 3/4	10.586	71	154.3	112.8

Table 12: Wellbore dimensions for 2,000m (Target TVD: 3,000m).

	3,000m wellbore						
Section	Setting depth [m]	Section length [m]	OD [inch]	ID [inch]	Casing weight/foot [lb/ft]	Cuttings [m^3]	Cement [m^3]
Bit size	-	-	20	-	-	-	-
Surface Casing	600	600	16	15.124	109	121.6	87.5
Bit size	-	-	14 3/4	-	-	-	-
Production casing	3,000	3,000	11 3/4	10.586	65.7	264.5	193.3

Table 13: Wellbore dimensions for 3,000m (Target TVD: 3,000m).

8.3 3,000m Subsurface Wellbore (Target TVD: 4,000m)

A second scenario — with the idea of a multiple wellbore out of a single cavern, as in 8.2 was created. The main difference between those scenarios is the deeper wellbore depth of 4,000m in this design. The production casing is marginally smaller than in the previous scenario, with an outer diameter of 10 3/4”. The surface casing diameter of 16” stays the same (Figure 27).

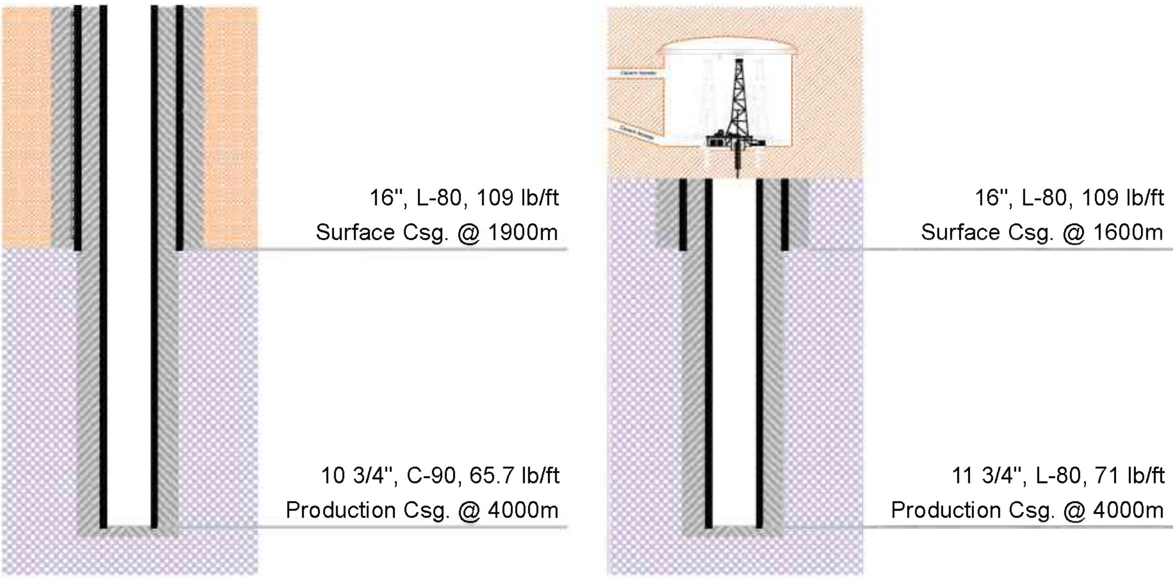


Figure 27: Casing Design TD 4,000m – surface (left) and subsurface (right)

Table 14 and Table 15 shows the casing and bit dimensions for a 3,000m wellbore and a 4,000m one, respectively.

	3,000m wellbore, subsurface						
Section	Setting depth [m]	Section length [m]	OD [inch]	ID [inch]	Casing weight/foot [lb/ft]	Cuttings $[m^3]$	Cement $[m^3]$
Bit size	-	-	20	-	-	-	-
Surface Casing	1,600	600	16	14.688	75	121.6	264.5
Bit size	-	-	14 3/4	-	-	-	-
Production casing	4,000	3,000	10 3/4	9.660	71	87.5	248.0

Table 14: Wellbore dimensions for 3,000m (Target TVD: 4,000m).

	4,000m wellbore						
Section	Setting depth [m]	Section length [m]	OD [inch]	ID [inch]	Casing weight/foot [lb/ft]	Cuttings $[m^3]$	Cement $[m^3]$
Bit size	-	-	20	-	-	-	-
Surface Casing	1900	1900	16	14.688	109	385.0	231.4
Bit size	-	-	14 3/4	-	-	-	-
Production casing	4,000	4,000	10 3/4	9.560	65.7	277.2	217.0

Table 15: Wellbore dimensions for 4,000m (Target TVD: 4,000m).

9 Economic Project Evaluation

To obtain a thorough understanding of the influencing factors on the individual contributing costs, an economic evaluation was conducted. It intended to determined whether a conventional wellbore, drilled from the Earth's surface, or one located on a subsurface level, is the economically more favorable solution.

Therefore, several scenarios were prepared and evaluated. Each scenario has a common target bottomhole depth and includes two cases — one for a conventional surface-located wellbore, whereas the other one represents a wellbore with a subsurface starting point 1,000m below ground.

9.1 Drilling Costs

Based on experience, the costs for drilling a deep wellbore represent the largest portion of the total costs of a geothermal system. The shares vary widely between 40% (Augustine, Tester, & Anderson, 2006), 50+% (Randeberg, et al., 2012) and 40 to 95% (Thorhallsson & Sveinbjornsson, Geothermal Drilling Cost and Drilling Effectiveness, 2012), according to reference costs in the literature. Such a vast fluctuation in costs is caused mainly by the uncertainty of geologic data in a project. Moreover, the costs are not equally spread all over the world. In remote areas, higher fees are charged by the contractors.

There is little complimentary data about geothermal drilling costs available, especially for the European region. Hence, the industry makes use of data from the oil and gas industry, where several thousand wells are drilled and reported each year. The use of oil and gas drilling data is valid, since the equipment and technology used is the same, although expenditures for geothermal wells are higher by the factor two to five compared to hydrocarbon wells. The reasons, therefore, are larger wellbore diameters, and the consequential higher amounts of expensive thermal-conductive cement and completion material. Hard and abrasive crystalline rocks are another reason for the increased costs. The drilling process is slowed down by lower associated ROP and frequent changes of the worn-out drill bit. Thus, the costs increase further.

While observing a statistically significant amount of deep wellbores, one can conclude that the costs are increasing exponentially with depth (Thorhallsson & Sveinbjornsson, Geothermal Drilling Cost and Drilling Effectiveness, 2012). This anomaly can be explained by the following contributing factors:

- The number of required casing strings increased with depth
- Drilling rig must consequentially handle higher loads
- Costs of additional casings and cement
- Lower ROP due to increasing strength and abrasiveness of deeper formations

Examples for the behavior of drilling cost with depth include a 5,000m vertical wellbore in France. By the use of an additional casing string (five instead of initially four), the overall costs rose by 18.5%. Another additional casing string raised the total costs by another 24%.

The cost behavior as a function of depth was also the concern of a study (Massachusetts Institute of Technology, 2006). Figure 28 displays the cost of completed geothermal and oil and gas wells in the US as a function of depth.

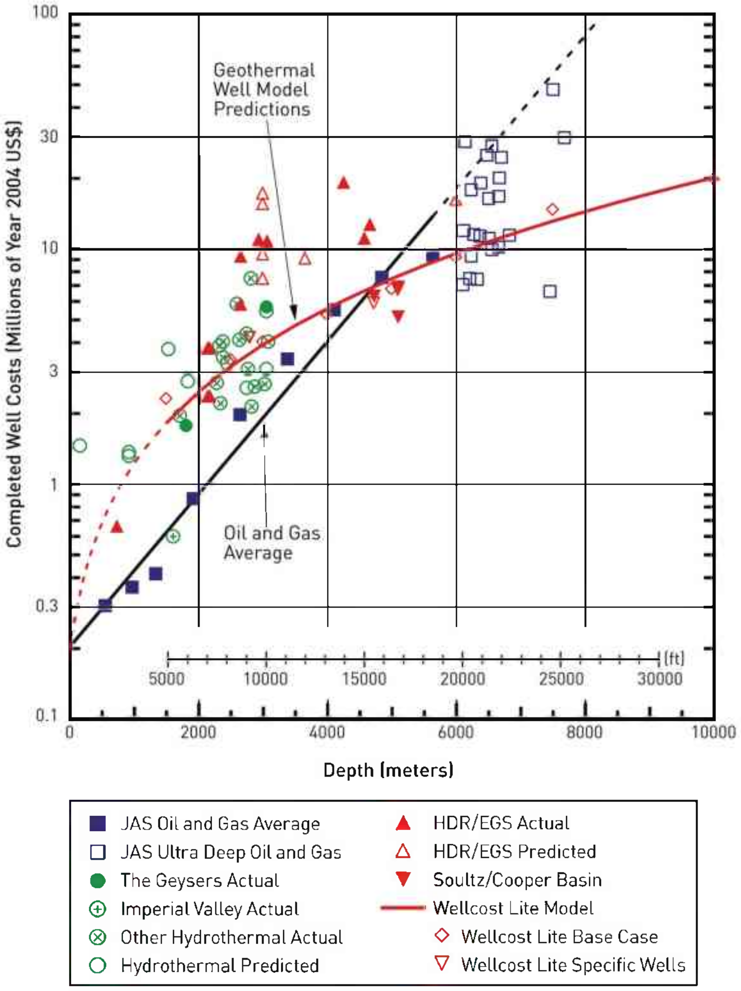


Figure 28: Completed geothermal oil and gas well costs as a function of depth (Massachusetts Institute of Technology, 2006)

9.1.1 Reference Wells

To obtain a first estimate for the expected costs, oil and gas well that had already been drilled as well as geothermal wells were researched. Only wellbores with a total depth of approximately 5,000m, the optimum depth of the project's well, were considered.

Annually published reports (American Petroleum Institute, 2003) by the API for oil and gas wells in North America provide a profound basis. The average expenditures in the year 2003 for deep wellbores between 4,572 and 5,333m amounted to 5.168 million USD (Thorhallsson & Sveinbjornsson, Geothermal Drilling Cost and Drilling Effectiveness, 2012). Further examples are the EGS wells GPK-3 and GPK-4 in Soultz, France. They are targeting a bottomhole depths of 5,101 and 5,100m, respectively. Even though the wellbores reach the same depth and were drilled in near vicinity of each other, the drilling costs vary widely. GPK-3 cost 6.571 million USD to drill, whereas GPK-4 cost just 5.14 million USD. A reason for the difference in cost may be local variations in geology, which frequently lead to drilling problems. These problems can only be overcome by intensive use of expensive technology and material. Not considered is the price increase since the year 2000, especially in the materials sector.

9.1.2 Cost Drivers

Drilling a deep wellbore is a complex undertaking. Consequently, the contributing factors for the total costs are versatile. A way of dividing the costs is into the origin of costs. The first main category comprises of costs for facilities, machinery and equipment as well as services. Materials, consumables and energy sources constitute the second main cost category.

9.1.2.1 Rental of Facilities, Machinery and Equipment, Services

Rental of facilities, machinery and equipment, and services comprises the first main category of costs. Customarily, these needs are leased for the individual work stages or kinds of service contractors. The contractors are then also responsible for conducting the work.

Construction of wellsite

The central part of the wellsite construction is the construction of a cavern. In the best case, the location for the cavern is in the middle of a mining area of valuable resources. Then, the cavern can be built within the scope of regular mining activities. Accruing costs would be reduced to a minimum. Additionally, the construction of access roads (if not already in place) and overhaul costs must be considered. For fresh air and energy supplies, supply shafts must be constructed.

Transportation

Transportation to and from the wellsite for each facility, machinery, equipment, materials and personnel.

Drilling rig

Daily rental costs for the drilling rig, equipment and operational personnel are included.

Project engineering, project management

Costs for design of the entire project. Planning, personnel and project management costs for the overall duration of the project.

Fluid and solids control equipment

Processing of drilling mud is commonly outsourced to a contractor. The contractor provides a mud engineer and the required facilities for solids separation and fluid preparation. Daily rates plus a one-off rental charge.

Directional drilling

Since there is a possibility of using directional drilling systems, two available systems are mentioned. PDM or RSS can be used; they are each charged on the basis of a daily rate. However, the planned wellbore is vertical, and therefore, there is no need for a directional drilling system.

Cementation

Includes material cost of cement, as well as the execution of the cement job. Cementing is usually done by a contractor in lieu of a daily charge.

Borehole geophysics

Geophysical wellbore measurements comprise, among others, caliper, resistance, density, and GR measurements.

Tools

Various tools that are necessary for the successful operation of the drilling rig and its maintenance, e.g. casing running tool.

Well control

Costs for well control equipment are included in the rental for the drilling rig.

Communication, surveillance

Sensors for surveillance and reporting of the individual working steps during drilling. Communication tools for ordinary phone calls and data transfer.

Perforation, stimulation, coiled tubing

Perforation with subsequent stimulation of the wellbore is not considered, since the geothermal well will be a closed system and no communication with the formation is desirable.

Cuttings disposal cost

Costs of the accruing cuttings during the drilling process that must be disposed. The cuttings are contaminated by the drilling mud and its additives.

9.1.2.2 Materials and Consumables

The second main category of drilling costs consists of material costs, costs for operational consumables and energy costs.

Drill bit

A drill bit has a certain durability and possibly needs to be changed several times while drilling the wellbore. Hard and abrasive formations make a replacement quite common.

Casing and tubing

Each section is cased with an (alloyed) carbon steel pipe. Costs are made up of used steel quality and pipe diameter. The same is true for the tubing, if it is composed of steel.

Casing accessories

Casing accessories mean, for instance, casing centralizers, linger hanger or floating shoe.

Wellhead

In the wellhead, each casing string and the tubing is hung off via casing and tubing spools.

Energy

Costs for overall energy required during the entire drilling process — predominantly, diesel and electricity.

9.2 Cost Evaluation

On the basis of the governing factors in 9.1.2, all contributing costs were researched. For those components where no costs could be determined, the figures were ascertained on the basis of experience.

Overall drilling costs are affected by various parameters throughout the entire process. Geology can be defined as the main factor dominating variations. Even with an accurate knowledge of the expected geology that is going to be drilled, the uncertainty of the financial outcome of the project is still high. Cost overruns are quite common in oil and gas drilling due to geological reasons. Hard, abrasive formations, as they are prevailing in the project region investigated, demand high investments into proper drilling equipment since those formations increase the wear of tools, accompanied by a slow drilling progress versus depth. Therefore, a first cost evaluation will only indicate a direction where the final costs are heading, and should be used with particular caution.

9.2.1 5,000m Subsurface Wellbore (Target TVD: 6,000m)

The minimum required footprints of several drilling rigs were assessed in 4.2 and 4.4: a length of 40m, width of 30m and a total height of 45m. Expected costs for excavation of a cubic meter rock is approx. 80 EUR (Galler, Estimated costs for excavation of a subsurface cavern, 2015), which results in a total of 4,320,000 EUR. This estimation is contrary to the costs associated with the construction of a surface well-site of 200,000 EUR.

Table 16 compares the costs of a 6,000m wellbore drilled from the surface with a 5,000m wellbore, drilled from the inside of a cavern.

COSTS PER SECTION	6,000m surface	5,000m subsurface
Base Costs	454.795	454.795
Section 1 — Surface	336.866	336.866
Services	125.913	125.913
Material and Consumables	210.953	210.953
Section 2 — Intermediate	2.547.348	2.547.348
Services	1.307.843	1.307.843
Material and Consumables	1.239.505	1.239.505
Section 3 — Production	4.001.552	2.898.135
Services	2.613.063	1.853.245
Material and Consumables	1.388.489	1.044.890
Total Drilling Costs	7.340.561	6.237.144
Difference		-1.103.417
Wellsite Construction Costs	200.000	4.320.000
Total Costs	7.540.561	10.557.144
Difference		3.016.583

Table 16: Comparison of a 6,000m wellbore — surface vs. subsurface drilled

The calculation can be separated in two parts. In the first part, the total costs for drilling a well are evaluated and compared. One can see that the 6,000m wellbore from the surface is almost 18% more expensive than its 5,000m counterpart, which is drilled from subsurface. A breakdown of drilling costs, divided into categories in accordance with the classification in 9.1.2, is shown in Table 18.

An important cost factor, which has not been considered so far in the calculation, includes the costs for the construction of the wellsite. In the case of the subsurface well, the costs for the cavern construction are added to the total drilling costs, whereas for the surface well, the ordinary well-site construction costs are added. With this information, the result has been inverted, and seems to be no longer economically attractive. But this will only be the case if the entire cavern has to be constructed from scratch. If a part of the required cavern space is already available in the mine, the costs for construction will be reduced by a certain amount. Even more favorable will be the situation with a subsurface wellsite within the value minerals. The mine operator will, nevertheless, excavate the minerals, so it can be done in a fashion to create the required cavern space for later conversion to a wellsite. In this specific scenario, the costs will be reduced to a minimum and the construction of a subsurface geothermal well can be done in a financially feasible and beneficial manner, compared to a common surface wellbore.

9.2.2 2,000m Subsurface Wellbore (Target TVD: 3,000m)

A similar economic evaluation was conducted with a pair of wellbores targeting a TVD of 3,000m. The results are shown in Table 17, and a detailed cost overview is given in Table 19.

COSTS PER SECTION	6,000m surface	5,000m subsurface
Base Costs	413.955	413.955
Section 1 — Surface	633.140	633.140
Services	254.893	254.893
Material and Consumables	378.246	378.246
Section 2 — Production	3.478.925	2.347.244
Services	1.765.105	1.127.651
Material and Consumables	1.713.821	1.219.592
Total Drilling Costs	4.526.020	3.394.339
Difference		-1.131.681
Wellsite Construction Costs	200.000	4.320.000
Total Costs	4.726.020	7.714.339
Difference		2.988.319

Table 17: Comparison of a 6,000m wellbore — surface vs. subsurface drilled

The same conclusion can be drawn for this case as for the case mentioned in 9.2.1: construction of a cavern is only economical if there are special conditions prevailing in the part of the mine and its operator company.

COST CATEGORIES	6,000m surface	5,000m subsurface
EQUIPMENT RENTAL AND SERVICES		
Trucking and Transportation	**50.000**	**50.000**
Estimate	50.000	50.000
Rig Mobilization/Demobilization	**50.000**	**50.000**
Estimate	50.000	50.000
Contract Drilling Rig	**2.551.695**	**2.072.597**
Rig Day Rate	2.551.695	2.072.597
Planning, Engineering, Project Management	**200.000**	**200.000**
Estimate	200.000	200.000
Drilling Fluids and Solids Control	**200.803**	**184.186**
Surface Section	21.130	21.130
Intermediate Section	79.659	79.659
Production Section	100.014	83.398
Cement and Services	**466.304**	**414.481**
Surface Section	18.581	18.581
Intermediate Section	255.979	255.979
Production Section	191.744	139.921
Geologic Evaluation and Reservoir Engineering	**892.753**	**725.133**
MWD/GR incl. Personnel	212.641	172.716
LWD PDM (GR/RES/Azimuth)	680.112	552.416
Drilling Tools Rental and Repair	**607.620**	**494.521**
Casing Running Tool — Overhead	5.250	5.250
Casing Running Tool — Operating	3.357	2.966
Casing Running Tool — Standby	599.013	486.305
Well Control Equipment Rental and Services	*Included in Rig Day Rate*	
MATERIALS AND CONSUMABLES		
Bits	**1.060.000**	**940.000**
Surface Section	110.000	110.000
Intermediate Section	500.000	500.000
Production Section	450.000	330.000
Casing and Tubing	**661.830**	**586.520**
Conductor	15.695	15.695
Surface Casing	38.472	38.472
Intermediate Casing	264.238	264.238
Production Liner	263.585	188.275
Tubing	79.840	79.840
Casing Accessories	**121.272**	**121.272**
Centralizer	6.700	6.700
Centralizer Make-up	1.571	1.571
Float Shoe and Collar	6.000	6.000
Float Shoe and Collar	5.000	5.000
Liner Hanger	82.000	82.000
Sealstem	20.000	20.000
Production Equipment	**53.000**	**53.000**
Wellhead	53.000	53.000
Energy	**425.283**	**345.433**
Fuel, Electricity	425.283	345.433
Total Drilling Costs	7.340.560	6.237.144
Difference		-1.103.417

Table 18: Breakdown and comparison of drilling costs for a wellbore with a target TVD of 6,000m

COST CATEGORIES	3,000m surface	2,000m subsurface
EQUIPMENT RENTAL AND SERVICES		
Trucking and Transportation	**50.000**	**50.000**
Estimate	50.000	50.000
Rig Mobilization/Demobilization	**50.000**	**50.000**
Estimate	50.000	50.000
Contract Drilling Rig	**1.273.697**	**871.754**
Rig Day Rate	1.273.697	871.754
Planning, Engineering, Project Management	**200.000**	**200.000**
Estimate	200.000	200.000
Drilling Fluids and Solids Control	**192.117**	**142.081**
Surface Section	149.857	99.821
Production Section	42.260	42.260
Cement and Services	**439.943**	**262.742**
Surface Section	14.662	14.662
Production Section	425.281	248.080
Geologic Evaluation and Reservoir Engineering	**445.624**	**304.998**
MWD/GR incl. Personnel	106.141	72.646
LWD PDM (GR/RES/Azimuth)	339.483	232.352
Drilling Tools Rental and Repair	**305.927**	**211.042**
Casing Running Tool — Overhead	5.250	5.250
Casing Running Tool — Operating	1.405	1.015
Casing Running Tool — Standby	299.272	204.777
Well Control Equipment Rental and Services	*Included in Rig Day Rate*	
MATERIALS AND CONSUMABLES		
Bits	**815.000**	**615.000**
Surface Section	165.000	165.000
Production Section	650.000	450.000
Casing and Tubing	**459.695**	**459.695**
Conductor	15.695	15.695
Surface Casing	120.000	120.000
Production Casing	292.000	292.000
Tubing	32.000	32.000
Casing Accessories	**21.734**	**21.734**
Centralizer	5.350	5.350
Centralizer Make-up	1.384	1.384
Float Shoe and Collar	6.000	6.000
Float Shoe and Collar	9.000	9.000
Production Equipment	**60.000**	**60.000**
Wellhead	60.000	60.000
Energy	**212.283**	**145.292**
Fuel, Electricity	212.283	145.292
Total Drilling Costs	4.526.020	3.394.339
Difference		-1.131.681

Table 19: Breakdown and comparison of drilling costs for a wellbore with a target TVD of 3,000m

9.3 Energy Yield of a Deep Geothermal Probe

To gain information about the economic efficiency of a petrothermal powered deep geothermal probe, an analysis of the prevailing geothermal potential must be conducted first.

Modeling of the thermal processes was done with a simulator developed by the Chair of Petroleum and Geothermal Energy Recovery at the Montanuniversitaet Leoben (Galler, et al., 2016). The simulator accounts for all geothermal processes in the region around the wellbore, as well as within the borehole. The heat losses in the formation are considered as transient, since the formation cools down with ongoing heat extraction during the operation of the deep geothermal probe. On the other hand, the processes taking place inside the borehole were defined as stationary; owing the fact that variations of the parameters occur on hourly or daily basis, compared to the transient heat losses that occur over a timespan of years. Both calculations, the transient and stationary, are paired via the temperature at the borehole wall.

Conduction, radiation and convection were considered as mechanism for heat transport. Heat conduction describes, according to Fourier's law, the transport of heat from a warmer location to a colder location. The process is irreversible. Further, kinetic energy is transferred without material transport. Heat conduction takes place in geological formations, also in casing, tubing and cement. At the interface of two different materials, a heat transfer coefficient must be considered. The second process, heat radiation, is based on heat transfer through electromagnetic waves. Hence, heat can be transferred through a vacuum. Every surface emits radiation; therefore, the resulting heat transfer is the difference of two opposing heat flows. Heat can also be transported by streaming fluids, which is then called heat convection, and the third process for heat transfer. Heat convection is caused by differences in pressure, density and temperature. In principle, a distinction between to different types on convection is made: forced and free convection. Forced convection happens when external forces are acting on the fluid, whereas free convection is mainly caused by thermal density differences (Galler, et al., 2016).

The influence of temperature on the circulating media – water – was also taken into account. Water properties, such as density, heat capacity, Prandtl number, thermal conductivity and viscosity have a more or less strong impact on errors in the simulation. Most critical is the temperature dependence of conductivity, viscosity and Prandtl number.

9.3.1 Simulation of a Subsurface Wellbore – Perfect Conditions

For the first simulation, perfect conditions in and around the wellbore were assumed: there is a unique, homogenous geological formation; a 5,000m vertical wellbore, drilled into crystalline basement rock; the 8-inch hole is competent, hence no borehole completion is necessary; the tubing has an OD of 4 ½ inch and is perfectly isolated; the beginning of the wellbore is located at a depth of 1,000m, where a temperature of 30°C is present; a geothermal gradient of 3°C/100m results in a bottomhole temperature of 180°C; a rock density of 2,900kg/m^3, a heat capacity of 710W/kg°K, a thermal conductivity of 3W/m°K; a circulation rate of 10m^3/h and a flow temperature of 60°C.

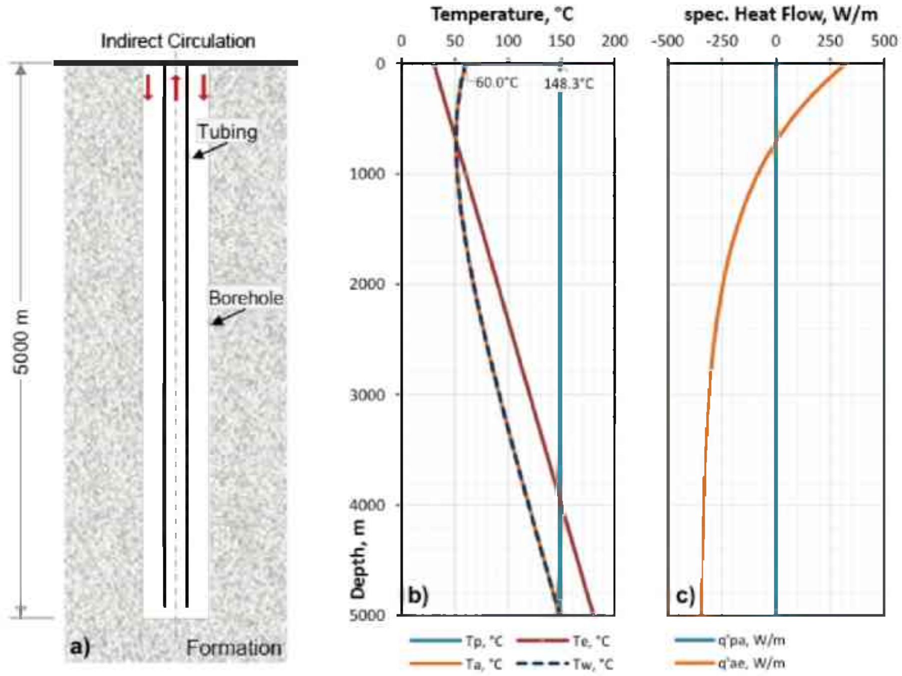


Figure 29: Subsurface wellbore, perfect conditions – beginning of indirect circulation (Galler, et al., 2016)

In Figure 29, the indirect circulation of a subsurface wellbore under perfect conditions is shown. Indirect circulation means that the circulation media is injected in the annulus between formation and tubing. The return flow to the surface takes place inside the tubing. The red line (Figure 29b) represents the initial formation temperature. The orange curve, which represents the temperature of the fluid in the annulus, is identical with the dashed dark-blue curve, which represents the temperature along the borehole wall. The temperature of the fluid inside the tubing (blue curve) is constant over the the entire tubing length, since a perfect isolation is applied. In this setting, with a flow temperature of 60°C, a return flow temperature of 148.3°C can be obtained.

Figure 30 shows the temperature regimes after 30 years of indirect circulation. The formation has cooled down due to heat extraction and the return flow temperature sunk down to 103.8°C. A direct result of the alteration of formation temperatures during operation is the energy output. After one year of operation, only 63% and after 30 years, only the half of the initial present energy can be utilized.

Since the simulation was run for a completely homogeneous geological formation and uniform completion materials, a parameter study was carried out to account for variations. Results show that the energy, which can be extracted, goes in accordance with the fluid circulation rate. A higher circulation rate leads to a higher energy output. But, the formation will cool down faster, and the return flow temperature will be lower compared to a moderate circulation rate. Furthermore, alterations in thermal conductivity have a larger impact on the result than changes in heat capacity.

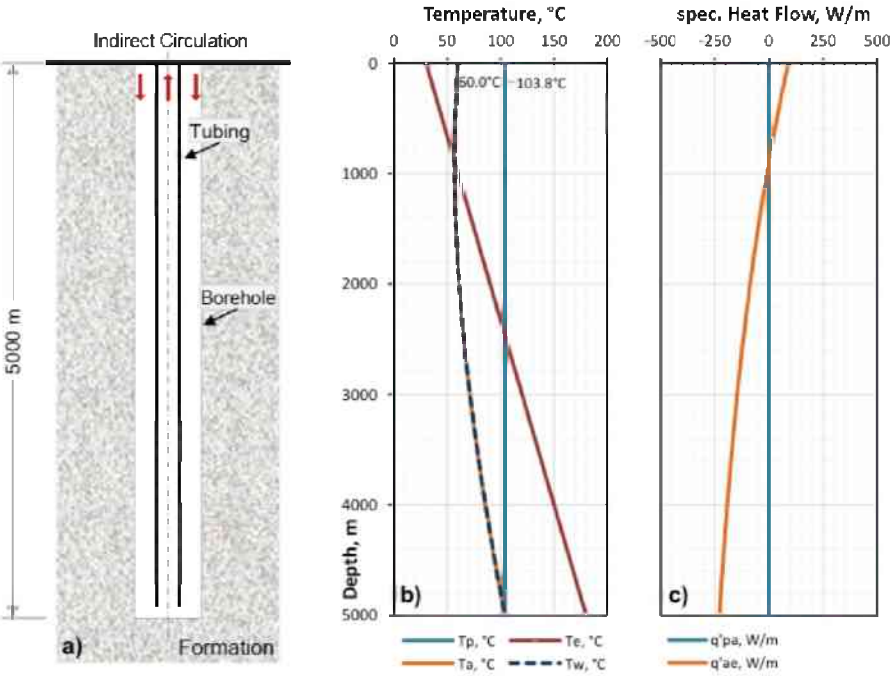


Figure 30: Subsurface wellbore, perfect conditions – 30 years of indirect circulation (Galler, et al., 2016)

9.3.2 Simulation of a Subsurface Wellbore – Real Conditions

This simulation assumes similar conditions as in 9.3.1, except the borehole completion. Instead of no installed casing, the completion consists of a surface and intermediate casing, followed by a production liner. The return flow temperature reaches now 144°C, compared to 148.3°C in the case with perfect conditions. The discontinuities of the heat flow (orange curve, Figure 31c) result from changes of the thermal resistance in zones of casing changes.

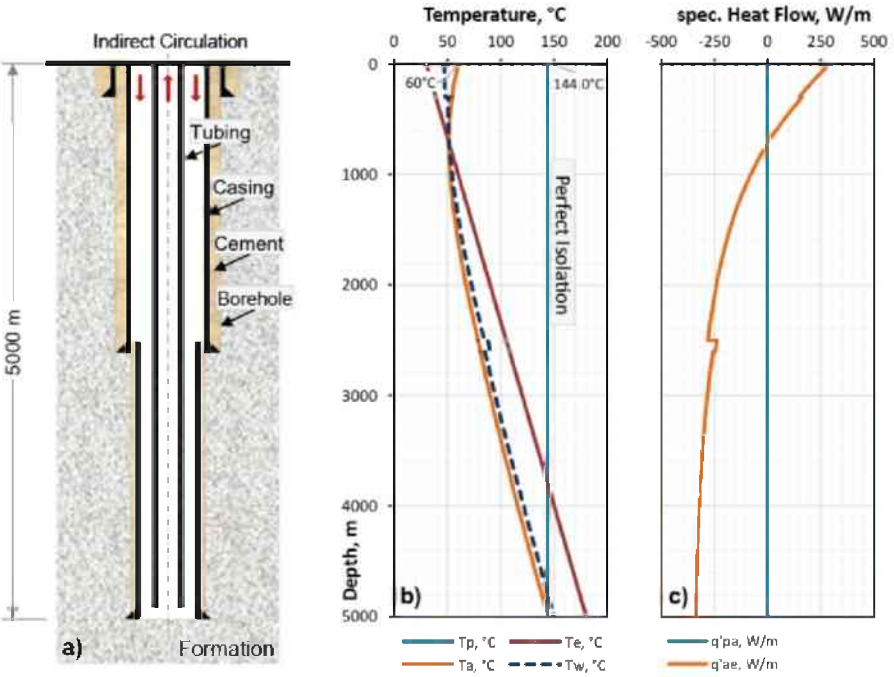


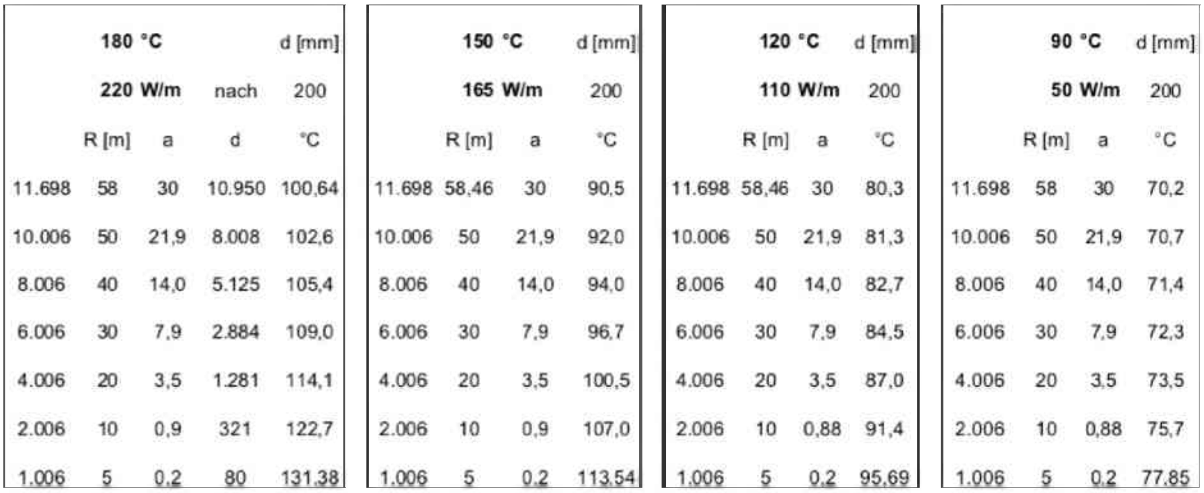
Figure 31: Subsurface wellbore, real conditions – beginning of indirect circulation (Galler, et al., 2016)

To summarize both cases, the one with perfect conditions and the one with real conditions, there is not much difference in the return flow temperature. Temperatures of both cases, especially the resulting temperatures after 30 years of operation, are too low to efficiently generate electricity. For such low temperatures the efficiency of a conversion to electricity is only around 10%. It is more useful to utilize the geothermal energy for heating purposes.

9.3.3 Rough Calculation of the Heat Extraction

In order to give an estimate about the cost/benefit ratio of deep geothermal probes, calculations under ideal conditions in a homogenous geological formation were performed. Following parameters were assumed: a geothermal gradient of 30°K/1,000m; thermal conductivity of 2.8W/m°K; heat capacity of 3.1MJ/m^3°K; and a heat flux in the earth of 75mW/m^2. A natural regeneration of the formation through the heat flux from the Earth's core is only limited, and, therefore, neglected in the calculation.

Four different depths with corresponding initial temperatures and local heat flows were selected for the calculations (Figure 32). All calculations start at 2,000m, since at this depth the formation temperature of 60°C is equal to the temperature of the circulation media. Hence, heat from the formation is transferred to the water beyond this depth. From the first calculation, with an initial temperature of 180°C, it can be seen that the borehole wall temperature cools down from 180°C to 131.4°C within 80 days. After 7.9 years (2,884 days) the temperature is only 109°C and, at the end of simulation, after 30 years (10,950 days) the temperature reaches 100.6°C. This behavior can be observed for all four calculations. The radius from the borehole, where the temperature of the formation is not affected, increases from 5m after 80 days to 58.46m after 30 years of operation. Therefore, it can be concluded that if multiple wellbores are drilled next to each other, the minimum distance between them must be twice the radius of 58.46m in order to avoid mutual influence.



	180 °C			d [mm]
	220 W/m		nach	200
	R [m]	a	d	°C
11.698	58	30	10.950	100,64
10.006	50	21,9	8.008	102,6
8.006	40	14,0	5.125	105,4
6.006	30	7,9	2.884	109,0
4.006	20	3,5	1.281	114,1
2.006	10	0,9	321	122,7
1.006	5	0,2	80	131,38

	150 °C		d [mm]
	165 W/m		200
	R [m]	a	°C
11.698	58,46	30	90,5
10.006	50	21,9	92,0
8.006	40	14,0	94,0
6.006	30	7,9	96,7
4.006	20	3,5	100,5
2.006	10	0,9	107,0
1.006	5	0,2	113,54

	120 °C		d [mm]
	110 W/m		200
	R [m]	a	°C
11.698	58,46	30	80,3
10.006	50	21,9	81,3
8.006	40	14,0	82,7
6.006	30	7,9	84,5
4.006	20	3,5	87,0
2.006	10	0,88	91,4
1.006	5	0,2	95,69

	90 °C		d [mm]
	50 W/m		200
	R [m]	a	°C
11.698	58	30	70,2
10.006	50	21,9	70,7
8.006	40	14,0	71,4
6.006	30	7,9	72,3
4.006	20	3,5	73,5
2.006	10	0,88	75,7
1.006	5	0,2	77,85

Figure 32: Calculation points in 6,000m, 5,000m, 4,000m and 3,000m depth with corresponding initial temperatures of 180°C, 150°C, 120°C and 90°C and local heat flows of 220W/m, 165W/m, 110W/m and 50W/m (Galler, et al., 2016).

Assuming that the heat flow increases linear from a depth of 2,000m to 6,000m to a final value of 220W/m, the average heat flow from the formation to the wellbore is 109W/m or 435kW for the respective length. At the beginning of operation, the circulation rate is 4.68m^3/h and after 30 years 12.47m^3/h, in order to keep the energy output of 435kW constant. Around 25% of thermal losses will occur, which amount to approx. 109kW. The net themeral energy output equals therefore 326kW. At a price of 85 EUR/MWh and an operating time of 8760h per year, the earnings are 242,740 EUR/year.

For a section length of 2,000m, starting from a depth of 2,000m to a TVD of 4,000m, the average heat flow equals 52.5W/m or 105kW. Thermal losses of 20% are assumed for this scenario, which result in 21kW of losses. The resulting thermal energy is 84kW and can be sold for 62,546 EUR/year, assuming the same price and operating time as before.

Concluding, it is not economic to drill multiple shallower wells compared to a deeper one. Earnings of 242,740 EUR/year from heat extracted over a wellbore length of 4,000 (6,000m TVD) are almost four-times higher than the 62,546 EUR/year revenue from a section length of 2,000m (4,000m TVD). Although, the costs for a shallower wellbore are reduced.

10 Conclusion

The declared objective of the study conducted within the scope of this thesis was to identify whether geothermal energy can be recovered from already existing subsurface facilities in a technically feasible, safe and economical manner. Therefore, a wellbore was designed in accordance with the general rules of oil and gas well design, with consideration for particular features of geothermal wells. The focus was on logistics, mainly on how to transport and set up the required equipment under restricted spatial conditions. HSE considerations were taken up. The financial feasibility of such a project was evaluated by various wellbore configurations.

Altogether, the results from the present study are promising for a successful implementation of a deep geothermal probe within a cavern, but with restrictions.

There are plenty of locations where such a project can be realized in Austria, and a specific mine in Styria, between the cities Graz and Bruck an der Mur, could be identified. The mine is active, and, thus, in good condition. Furthermore, the mine is located near a town that can benefit from the potentially extracted thermal energy. Owing to the ongoing period of low oil prices for 2016, drilling rigs have lots of spare capacity for new projects, at a decrease rig day rate compared to the preceding years. Modular rigs can be disassembled easily to transport in standardized units. In combination with trucks and flatbed trailers, those units will fit into and along the galleries of the investigated project mine. Heavy-duty cranes for unloading the equipment can also access the mine without restrictions. Drilling below the Earth’s surface will not influence residents or other surroundings by noise pollution; moreover, drilling operations are not visible to the public. Another benefit is the renunciation of the construction site renaturation. The location of the wellbore top far below the surface neglects the fluctuating temperature effect in the day and at nighttime, summer and winter, in the near surface area. A constant elevated temperature is present in the cavern. Drilling technology for a faster progress in hard formations is permanently under research; some promising technologies are already available and have showed proven success in field tests. The use of borehole heat exchangers as a method of energy recovery is independent of aquifers or natural fractured networks in the formation and so always applicable. Low OPEX and low maintenance are further features of this technology. A deep geothermal probe requires almost no workover if services for construction were properly conducted in first instance. Corrosion should also not be an issue in properly — and especially — continuously operated geothermal wells. The focus must lie on proper material selection, to ensure almost maintenance-free operation.

A clear disadvantage is the low amount of energy that will be recovered by using a deep geothermal probe compared to hydrothermal or other petrothermal systems. Only a few comparable systems have been implemented so far and all drilled in a conventional way from surface. The subsurface approach within a subsurface facility is economically feasible only if the cavern or tunnel already exists. A cavern constructed only for the purpose of geothermal recovery will not financially justify the savings in 1,000m of wellbore. Possible synergies must be identified and utilized; only then will such a project will be financially feasible. Owing to incentives, the mine operator will mine the natural resources in such a way that a sufficient large cavern space remains for later geothermal usage.

Considerations must be made with regard to the legal aspects. A drilling rig has never been in operation below ground; a legal framework must be worked out in advance. Emergency exit concepts from the rig site must be thoroughly elaborated. Rig-up operations in that narrow space must be trained earlier, possibly during ordinary oil and gas drilling operations on land. Overbalanced drilling of the first few meters might be an additional challenge since it has never been done before, despite the fact that a reasonable solution exists. The benefits of a possible merger of the drilling rig with a portal crane in the cavern may be subject to further research.

Recommendations

To attain the goal, it is necessary to known more about the geological conditions in the project area. A seismic survey is definitely of advantage. The project presents various research opportunities in a region where lesser amounts of confirmed information are known about the geological composition in great depth. Further on, new drilling technologies can be developed and tested within the execution of such a pilot project. The public influence on the realization might be small, since the operation does not affect any parties, except for the mine operator. An implementation of a pilot project for this innovative idea may yield further incentives for successful geothermal energy extraction worldwide.

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11.4 Abbreviations

API	American Petroleum Institute
BHA	Bottom hole assembly
BHE	Borehole heat exchanger
BOP	Blow out preventer
CAPEX	Capital expenditure
ESP	Electric submersible pump
EUA	European Union allowance
EU ETS	European Union emissions trading system
GR	Gamma ray
GRP	Glass fiber reinforced plastic
HSE	Health, safety, environment
ID	Inner diameter
OD	Outer diameter
ORC	Organic Rankine Cycle
PDC	Polycrystalline diamond compact
PDM	Positive displacement motor
RAG	Rohöl-Aufsuchungs Gesellschaft
ROP	Rate of penetration
RSS	Rotary steering system
SL	Sea level
TCI	Tungsten carbide inserts
TVD	True vertical depth
UCS	Unconfined compressive strength
WOB	Weight on bit

Appendix A

No.	Description	Dimensions L x W x H [mm]	Container [ft]	Weight [kg]
1	Transporteinheit Quer-Container	12.192 x 2.438 x 2.896	40	25.900
2	Transporteinheit Abstütz-Container D-Seite	12.192 x 2.438 x 2.822	40	36.100
3	Transporteinheit Abstütz-Container B-Seite	12.192 x 2.438 x 2.822	40	38.100
4	Transporteinheit Pumpenrahmen	12.192 x 2.438 x 2.896	40	15.665
5	Hydraulikaggregat	12.192 x 2.438 x 2.896	40	39.000
6	Aufstell-Container mit A-Bock	12.192 x 2.438 x 2.896	40	49.100
7	Transporteinheit Winden-Container	11.400 x 2.438 x 2.896	40	27.500
8	Transporteinheit Hauptwinde	4.050 x 1.950 x 2.050	20	11.800
10	Transporteinheit Nackenstütze	11.893 x 1.730 x 2.450	40	10.650
11	Transporteinheit Mastfuß	12.192 x 2.438 x 1.835	40	40.920
12	Transporteinheit Mastunterteil	12.192 x 2.438 x 1.835	40	19.400
13	Transporteinheit Mastverlängerung	12.192 x 2.438 x 1.835	40	17.200
14	Transporteinheit Mastoberteil	6.058 x 2.438 x 2.500	20	9.500
15	Transporteinheit Blow Out Preventer	6.058 x 2.438 x 2.500	20	14.350
16	Kabine	4.120 x 2.700 x 3.100	Special	4.500
17	Dog House	2.438 x 2.050 x 2.591	Special	2.500
18	Mess-Container	3.100 x 2.438 x 2.591	Special	2.000
19	Schallschutz-Container	3.800 x 2.438 x 2.591	Special	3.600
20	Drill Floor	12.192 x 2.438 x 2.896	40	28.000
21	Drill Floor Extension	12.192 x 2.438 x 2.050	40	11.000
22	VFD-Container	12.400 x 2.960 x 2.950	Special	24.000
23	Transporteinheit Gestängehandhabung Mast	12.192 x 2.438 x 2.591	40	25.000
24	Gestängetisch	11.400 x 2.050 x 2.300	40	5.800
25	Transporteinheit Vorschubschlitten	7.932 x 2.438 x 2.591	20	32.200
26	Kompressor	6.058 x 2.438 x 2.591	20	4.000
27	Transporteinheit Windschutzwände	6.058 x 2.438 x 2.591	20	5.000
28	Transporteinheit Windschutzwände und Beleuchtungseinrichtung	12.192 x 2.438 x 2.896	40	10.000
29	Transporteinheit Begehungen 1	12.192 x 2.438 x 2.896	40	12.500
30	Spülpumpe 1	6.058 x 2.438 x 2.591	20	30.000
31	Spülpumpe 2	6.058 x 2.438 x 2.591	20	30.000
32	Spülpumpe 3	6.058 x 2.438 x 2.591	20	30.000
33	Spülpumpe 4	6.058 x 2.438 x 2.591	20	30.000
35	Schließanlage	6.058 x 2.438 x 2.591	20	6.500
36	Transporteinheit Fackel	2.991 x 2.438 x 2.591	10	2.520
37	Transport-Container Begehungen 2	12.192 x 2.438 x 2.591	40	8.700
38	Transport-Container Begehungen 3	12.192 x 2.438 x 2.591	40	15.427
39	Transporteinheit Skidding-System 1	6.058 x 2.438 x 2.591	20	17.700
40	Transporteinheit Skidding-System 2	6.058 x 2.438 x 2.591	20	20.300
41	Transporteinheit Skidding-System 3	6.058 x 2.438 x 2.591	20	20.500
42	Transporteinheit Hydraulikverrohrungsrahmen	12.192 x 2.438 x 2.591	40	5.345
43	Transporteinheit Reserve Top Drive	6.058 x 2.438 x 2.591	20	11.500
44	Generator-Container 1	12.192 x 2.438 x 2.896	40	24.000
45	Generator-Container 2	12.192 x 2.438 x 2.896	40	24.000
46	Generator-Container 3	12.192 x 2.438 x 2.896	40	24.000
47	Hilfsgenerator	6.058 x 2.438 x 2.591	20	6.900
48	Kabelkiste	12.192 x 2.438 x 2.591	40	7.000
49	Transporteinheit Personenbeförderung	6.058 x 2.438 x 2.591	40	750
50	Kleinteile	12.192 x 2.438 x 2.591	40	20.000
51	Kleinteile	12.192 x 2.438 x 2.591	40	18.580
52	Werkzeuge und Batterie	3.029 x 2.438 x 2.591	10	8.000
53	Ersatzteile	12.192 x 2.438 x 2.591	40	15.000
54	Ersatzteile	12.192 x 2.438 x 2.591	40	15.000
55	Kleinteile	12.192 x 2.438 x 2.591	40	12.240

Table 20: List of all Bauer TBA 300 transport units.

Appendix B

5,000m Subsurface Wellbore — Standard Clearance

Setting Depth and EMW		Depth @ Csg. Shoe		EMW @ Csg. Shoe		
Section	Diameter	TVD	MD	Pore EMW	Mud EMW	Frac EMW
	[in]	[m]	[m]	[kg/m3]	[kg/m3]	[kg/m3]
Surface Casing	13 3/8	1300	300	1000	1030	1739
Intermediate Casing	9 5/8	3600	2600	1000	1030	1739
Production Liner	7	6000	5000	1000	1030	1739

Additional Data		
Parameter	Value	Unit
Steel Density	7850	kg/m3
Gas Gradient	0,02262	bar/m

Design Factors	
Collapse	1,00
Burst	1,10
Tension	1,60

Calculation of the Expected Loads						
Section	Surface Casing		Intermediate Casing		Production Casing	
	[bar]	[psi]	[bar]	[psi]	[bar]	[psi]
Outside Pressure Profile						
Mud Column	131	1905	364	5276	606	8793
Inside Pressure Profile for Burst (effective at the Wellhead)					(at Liner Hanger)	
Max. Possible Shut-in Pressure	192	2790	533	7726	-	-
Wellhead Pressure is 40% of BHP	-	-	146	2110	-	-
Full Gas Column	-	-	453	6568	534	7750
Inside Pressure Profile for Collapse (effective at the Wellhead)						
Inside Partially Empty	122	1766	112	1619	-	-
Inside Empty	-	-	-	-	1	15
Resulting Loads						
Resulting Load Burst	192	2790	533	7726	171	2474
Burst Load incl. DF	212	3069	586	8498	188	2721
Resulting Load Collapse	10	139	252	3656	606	8793
Collapse Load incl. DF	10	139	252	3656	606	8793

Casing Selection						
Grade	**M-55**		**P-110**		**L-80**	
OD	**13 3/8**	in	**9 5/8**	in	**7**	in
Weight per Foot	**61**	lb/ft	**53,5**	lb/ft	**35**	lb/ft
	90,78	kg/m	79,62	kg/m	52,09	kg/m
ID	12,415	in	8,535	in	6,004	in
Coupling	STC		LTC		LTC	
Burst Resistance	3660	psi	10900	psi	9240	psi
(Internal Yield Pressure, psi)	252	bar	752	bar	637	bar
Burst incl. Temperature Effect	220	bar	654	bar	554	bar
Collapse Resistance	1620	psi	7950	psi	10180	psi
(Collapse Resistance, psi)	112	bar	548	bar	702	bar
Yield Strength	697	1000 lb	1422	1000 lb	734	1000 lb
(Joint Strength, 1000lb)	3100	kN	6325	kN	3265	kN
Yield Str. incl. Temperature Effect	2697	kN	5503	kN	2840	kN
Control Calculation Burst						
Safety Factor	**1,14**	> 1.10	**1,12**	> 1.10	**2,95**	> 1.10
Control Calculation Collaps						
Safety Factor	**11,64**	> 1.00	**2,17**	> 1.00	**1,16**	> 1.00
Control Calculation Axial Tension						
Weight in Air	27.234	kg	207.006	kg	130.216	kg
Buoyancy Factor	0,869		0,869		0,869	
Weight in Fluid	23.660	kg	179.845	kg	113.130	kg
Safety Factor	**11,62**	> 1.60	**3,12**	> 1.60	**2,56**	> 1.60

5,000m Subsurface Wellbore — Low Clearance

Setting Depth and EMW

Section	Diameter	Depth @ Csg. Shoe		EMW @ Csg. Shoe		
		TVD	MD	Pore EMW	Mud EMW	Frac EMW
	[in]	[m]	[m]	[kg/m3]	[kg/m3]	[kg/m3]
Surface Casing	11 3/4	1300	300	1000	1030	1739
Intermediate Casing	9 5/8	3600	2600	1000	1030	1739
Production Liner	7	6000	5000	1000	1030	1739

Additional Data

Parameter	Value	Unit
Steel Density	7850	kg/m3
Gas Gradient	0,02262	bar/m

Design Factors

Collapse	1,00
Burst	1,10
Tension	1,60

Calculation of the Expected Loads

Section	Surface Casing		Intermediate Casing		Production Casing	
	[bar]	[psi]	[bar]	[psi]	[bar]	[psi]
Outside Pressure Profile						
Flüssigkeitssäule Bohrspülung	131	1905	364	5276	606	8793
Inside Pressure Profile for Burst (effective at the Wellhead)					(at Liner Hanger)	
Max. Possible Shut-in Pressure	192	2790	533	7726	-	-
Wellhead Pressure is 40% of BHP	-	-	146	2110	-	-
Full Gas Column	-	-	453	6568	534	7750
Inside Pressure Profile for Collapse (effective at the Wellhead)						
Inside Partially Empty	122	1766	112	1619	-	-
Inside Empty	-	-	-	-	1	15
Resulting Loads						
Resulting Load Burst	192	2790	533	7726	171	2474
Burst Load incl. DF	212	3069	586	8498	188	2721
Resulting Load Collapse	10	139	252	3656	606	8793
Collapse Load incl. DF	10	139	252	3656	606	8793

Casing Selection

Grade	**J-55**		**P-110**		**L-80**	
OD	**11 3/4**	in	**9 5/8**	in	**7**	in
Weight per Foot	**54**	lb/ft	**53,5**	lb/ft	**35**	lb/ft
	80,36	kg/m	79,62	kg/m	52,09	kg/m
ID	10,880	in	8,535	in	6,004	in
Coupling	STC		LTC		LTC	
Burst Resistance (Internal Yield Pressure, psi)	3560	psi	10900	psi	9240	psi
	245	bar	752	bar	637	bar
Burst incl. Temperature Effect	214	bar	654	bar	554	bar
Collapse Resistance (Collapse Resistance, psi)	2070	psi	7950	psi	10180	psi
	143	bar	548	bar	702	bar
Yield Strength (Joint Strength, 1000lb)	568	1000 lb	1422	1000 lb	734	1000 lb
	2526	kN	6325	kN	3265	kN
Yield Str. incl. Temperature Effect	2198	kN	5503	kN	2840	kN

Control Calculation Burst

Safety Factor	**1,11**	> 1.10	**1,12**	> 1.10	**2,95**	> 1.10

Control Calculation Collaps

Safety Factor	**14,87**	> 1.00	**2,17**	> 1.00	**1,16**	> 1.00

Control Calculation Axial Tension

Weight in Air	24.109	kg	207.006	kg	130.216	kg
Buoyancy Factor	0,869		0,869		0,869	
Weight in Fluid	20.945	kg	179.845	kg	113.130	kg
Safety Factor	**10,70**	> 1.60	**3,12**	> 1.60	**2,56**	> 1.60

6,000m Surface Located Wellbore — Standard Clearance

Setting Depth and EMW

Section	Diameter	Depth @ Csg. Shoe TVD	Depth @ Csg. Shoe MD	EMW @ Csg. Shoe Pore EMW	EMW @ Csg. Shoe Mud EMW	EMW @ Csg. Shoe Frac EMW
	[in]	[m]	[m]	[kg/m3]	[kg/m3]	[kg/m3]
Surface Casing	13 3/8	300	300	1000	1030	1739
Intermediate Casing	9 5/8	2600	2600	1000	1030	1739
Production Liner	7	6000	6000	1000	1030	1739

Additional Data

Parameter	Value	Unit
Steel Density	7850	kg/m3
Gas Gradient	0,02262	bar/m

Design Factors

Collapse	1,00
Burst	1,10
Tension	1,60

Calculation of the Expected Loads

Section	Surface Casing		Intermediate Casing		Production Casing	
	[bar]	[psi]	[bar]	[psi]	[bar]	[psi]
Outside Pressure Profile						
Mud Column	30	440	263	3810	606	8793
Inside Pressure Profile for Burst (effective at the Wellhead)					(at Liner Hanger)	
Max. Possible Shut-in Pressure	44	644	385	5580	-	-
Wellhead Pressure is 40% of BHP	-	-	105	1524	-	-
Full Gas Column	-	-	453	6568	512	7421
Inside Pressure Profile for Collapse (effective at the Wellhead)						
Inside Partially Empty	24	343	-87	-1269	-	-
Inside Empty	-	-	-	-	1	15
Resulting Loads						
Resulting Load Burst	44	644	453	5580	249	3611
Burst Load incl. DF	49	708	498	6138	274	3972
Resulting Load Collapse	7	96	350	5079	606	8793
Collapse Load incl. DF	7	96	350	5079	606	8793

Casing Selection

Grade	**J-55**		**S-95**		**L-80**	
OD	**13 3/8**	in	**9 5/8**	in	**7**	in
Weight per Foot	**68**	lb/ft	**53,5**	lb/ft	**35**	lb/ft
	101,20	kg/m	79,62	kg/m	52,09	kg/m
ID	12,415	in	8,535	in	6,004	in
Coupling	STC		LTC		LTC	
Burst Resistance (Internal Yield Pressure, psi)	3450	psi	9410	psi	9240	psi
	238	bar	649	bar	637	bar
Burst incl. Temperature Effect	207	bar	564	bar	554	bar
Collapse Resistance (Collapse Resistance, psi)	1950	psi	8850	psi	10180	psi
	134	bar	610	bar	702	bar
Yield Strength (Joint Strength, 1000lb)	675	1000 lb	1235	1000 lb	734	1000 lb
	3002	kN	5493	kN	3265	kN
Yield Str. incl. Temperature Effect	2612	kN	4779	kN	2840	kN

Control Calculation Burst

Safety Factor	**4,66**	> 1.10	**1,13**	> 1.10	**2,02**	> 1.10

Control Calculation Collaps

Safety Factor	**20,21**	> 1.00	**1,74**	> 1.00	**1,16**	> 1.00

Control Calculation Axial Tension

Weight in Air	30.359	kg	207.006	kg	182.303	kg
Buoyancy Factor	0,869		0,869		0,869	
Weight in Fluid	26.376	kg	179.845	kg	158.383	kg
Safety Factor	**10,10**	> 1.60	**2,71**	> 1.60	**1,83**	> 1.60

6,000m Surface Located Wellbore — Low Clearance

Setting Depth and EMW

Section	Diameter	Depth @ Csg. Shoe		EMW @ Csg. Shoe		
		TVD	MD	Pore EMW	Mud EMW	Frac EMW
	[in]	[m]	[m]	[kg/m3]	[kg/m3]	[kg/m3]
Surface Casing	11 3/4	300	300	1000	1030	1739
Intermediate Casing	9 5/8	2600	2600	1000	1030	1739
Production Liner	7	6000	6000	1000	1030	1739

Additional Data

Parameter	Value	Unit
Steel Density	7850	kg/m3
Gas Gradient	0,02262	bar/m

Design Factors

Collapse	1,00
Burst	1,10
Tension	1,60

Calculation of the Expected Loads

Section	Surface Casing		Intermediate Casing		Production Casing	
	[bar]	[psi]	[bar]	[psi]	[bar]	[psi]
Outside Pressure Profile						
Mud Column	30	440	263	3810	606	8793
Inside Pressure Profile for Burst (effective at the Wellhead)					(at Liner Hanger)	
Max. Possible Shut-in Pressure	44	644	385	5580	-	-
Wellhead Pressure is 40% of BHP	-	-	105	1524	-	-
Full Gas Column	-	-	453	6568	512	7421
Inside Pressure Profile for Collapse (effective at the Wellhead)						
Inside Partially Empty	24	343	-87	-1269	-	-
Inside Empty	-	-	-	-	1	15
Resulting Loads						
Resulting Load Burst	44	644	453	5580	249	3611
Burst Load incl. DF	49	708	498	6138	274	3972
Resulting Load Collapse	7	96	350	5079	606	8793
Collapse Load incl. DF	7	96	350	5079	606	8793

Casing Selection

Grade	**J-55**		**S-95**		**L-80**	
OD	**11 3/4**	in	**9 5/8**	in	**7**	in
Weight per Foot	**47**	lb/ft	**53,5**	lb/ft	**35**	lb/ft
	69,94	kg/m	79,62	kg/m	52,09	kg/m
ID	11,000	in	8,535	in	6,004	in
Coupling	STC		LTC		LTC	
Burst Resistance	3070	psi	9410	psi	9240	psi
(Internal Yield Pressure, psi)	212	bar	649	bar	637	bar
Burst incl. Temperature Effect	184	bar	564	bar	554	bar
Collapse Resistance	1510	psi	8850	psi	10180	psi
(Collapse Resistance, psi)	104	bar	610	bar	702	bar
Yield Strength	477	1000 lb	1235	1000 lb	734	1000 lb
(Joint Strength, 1000lb)	2122	kN	5493	kN	3265	kN
Yield Str. incl. Temperature Effect	1846	kN	4779	kN	2840	kN

Control Calculation Burst

Safety Factor	**4,15**	> 1.10	**1,13**	> 1.10	**2,02**	> 1.10

Control Calculation Collaps

Safety Factor	**15,65**	> 1.00	**1,74**	> 1.00	**1,16**	> 1.00

Control Calculation Axial Tension

Weight in Air	20.983	kg	207.006	kg	182.303	kg
Buoyancy Factor	0,869		0,869		0,869	
Weight in Fluid	18.230	kg	179.845	kg	158.383	kg
Safety Factor	**10,32**	> 1.60	**2,71**	> 1.60	**1,83**	> 1.60

Appendix C

2,000m Subsurface Wellbore (Target TVD: 3,000m)

Setting Depth and EMW		Depth @ Csg. Shoe		EMW @ Csg. Shoe		
Section	Diameter [in]	TVD [m]	MD [m]	Pore EMW [kg/m3]	Mud EMW [kg/m3]	Frac EMW [kg/m3]
Surface Casing	16	1600	600	1000	1030	1739
Production Casing	11 3/4	3000	2000	1000	1030	1739

Additional Data		
Parameter	Value	Unit
Steel Density	7850	kg/m3
Gas Gradient	0,02262	bar/m

Design Factors	
Collapse	1,00
Burst	1,10
Tension	1,60

Calculation of the Expected Loads						
Section	Surface Casing		Intermediate Casing		Production Casing	
	[bar]	[psi]	[bar]	[psi]	[bar]	[psi]
Outside Pressure Profile						
Mud Column	162	2345	-	-	303	4397
Inside Pressure Profile for Burst (effective at the Wellhead)						
Max. Possible Shut-in Pressure	237	3434	-	-	-	-
Full Gas Column	-	-	-	-	226	3284
Inside Pressure Profile for Collapse (effective at the Wellhead)						
Inside Partially Empty	154	2231	-	-	-	-
Inside Empty	-	-	-	-	1	15
Resulting Loads						
Resulting Load Burst	237	3434	-	-	226	3284
Burst Load incl. DF	260	3777	-	-	249	3613
Resulting Load Collapse	8	114	-	-	303	4397
Collapse Load incl. DF	8	114	-	-	303	4397
Casing Selection						
Grade	**L-80**				**L-80**	
OD	**16**	in	-	in	**11 3/4**	in
Weight per Foot	**109**	lb/ft	-	lb/ft	**71**	lb/ft
	162,21	kg/m	-	kg/m	105,66	kg/m
ID	14,688	in	-	in	10,586	in
Coupling	-		-		-	
Burst Resistance (Internal Yield Pressure, psi)	5740	psi	-	psi	6930	psi
	396	bar	-	bar	478	bar
Burst incl. Temperature Effect	344	bar	-	bar	416	bar
Collapse Resistance (Collapse Resistance, psi)	3080	psi	-	psi	4880	psi
	212	bar	-	bar	336	bar
Yield Strength (Joint Strength, 1000lb)	2530	1000 lb	-	1000 lb	1634	1000 lb
	11253	kN	-	kN	7268	kN
Yield Str. incl. Temperature Effect	9790	kN	-	kN	6323	kN
Control Calculation Burst						
Safety Factor	**1,45**	> 1.10	-	> 1.10	**1,67**	> 1.10
Control Calculation Collaps						
Safety Factor	**27,12**	> 1.00	-	> 1.00	**1,11**	> 1.00
Control Calculation Axial Tension						
Weight in Air	97.327	kg	-	kg	211.322	kg
Buoyancy Factor	0,869		-		0,869	
Weight in Fluid	84.557	kg	-	kg	183.594	kg
Safety Factor	**11,80**	> 1.60	-	> 1.60	**3,51**	> 1.60

3,000m Surface Located Wellbore (Target TVD: 3,000m)

Setting Depth and EMW

Section	Diameter	Depth @ Csg. Shoe		EMW @ Csg. Shoe		
		TVD	MD	Pore EMW	Mud EMW	Frac EMW
	[in]	[m]	[m]	[kg/m3]	[kg/m3]	[kg/m3]
Surface Casing	16	600	600	1000	1030	1739
Production Casing	11 3/4	3000	3000	1000	1030	1739

Additional Data

Parameter	Value	Unit
Steel Density	7850	kg/m3
Gas Gradient	0,02262	bar/m

Design Factors

Collapse	1,00
Burst	1,10
Tension	1,60

Calculation of the Expected Loads

Section	Surface Casing		Intermediate Casing		Production Casing	
	[bar]	[psi]	[bar]	[psi]	[bar]	[psi]
Outside Pressure Profile						
Mud Column	61	879	-	-	303	4397
Inside Pressure Profile for Burst (effective at the Wellhead)						
Max. Possible Shut-in Pressure	89	1288	-	-	-	-
Full Gas Column	-	-	-	-	226	3284
Inside Pressure Profile for Collapse (effective at the Wellhead)						
Inside Partially Empty	53	766	-	-	-	-
Inside Empty	-	-	-	-	1	15
Resulting Loads						
Resulting Load Burst	89	1288	-	-	226	3284
Burst Load incl. DF	98	1416	-	-	249	3613
Resulting Load Collapse	8	114	-	-	303	4397
Collapse Load incl. DF	8	114	-	-	303	4397

Casing Selection

Grade	**J-55**				**L-80**	
OD	**16**	in	-	in	**11 3/4**	in
Weight per Foot	**75**	lb/ft	-	lb/ft	**71**	lb/ft
	111,61	kg/m	-	kg/m	105,66	kg/m
ID	15,124	in	-	in	10,586	in
Coupling	-		-		-	
Burst Resistance (Internal Yield Pressure, psi)	2630	psi	-	psi	6930	psi
	181	bar	-	bar	478	bar
Burst incl. Temperature Effect	158	bar	-	bar	416	bar
Collapse Resistance (Collapse Resistance, psi)	1020	psi	-	psi	4880	psi
	70	bar	-	bar	336	bar
Yield Strength (Joint Strength, 1000lb)	710	1000 lb	-	1000 lb	1634	1000 lb
	3158	kN	-	kN	7268	kN
Yield Str. incl. Temperature Effect	2748	kN	-	kN	6323	kN

Control Calculation Burst

Safety Factor	**1,78**	> 1.10	-	> 1.10	**1,67**	> 1.10

Control Calculation Collaps

Safety Factor	**8,98**	> 1.00	-	> 1.00	**1,11**	> 1.00

Control Calculation Axial Tension

Weight in Air	66.968	kg	-	kg	316.983	kg
Buoyancy Factor	0,869		-		0,869	
Weight in Fluid	58.181	kg	-	kg	275.392	kg
Safety Factor	**4,81**	> 1.60	-	> 1.60	**2,34**	> 1.60

3,000m Subsurface Wellbore (Target TVD: 4,000m)

Setting Depth and EMW

Section	Diameter	Depth @ Csg. Shoe		EMW @ Csg. Shoe		
		TVD	MD	Pore EMW	Mud EMW	Frac EMW
	[in]	[m]	[m]	[kg/m3]	[kg/m3]	[kg/m3]
Surface Casing	16	1600	600	1000	1030	1739
Production Casing	10 3/4	4000	3000	1000	1030	1739

Additional Data

Parameter	Value	Unit
Steel Density	7850	kg/m3
Gas Gradient	0,02262	bar/m

Design Factors

Collapse	1,00
Burst	1,10
Tension	1,60

Calculation of the Expected Loads

Section	Surface Casing		Intermediate Casing		Production Casing	
	[bar]	[psi]	[bar]	[psi]	[bar]	[psi]
Outside Pressure Profile						
Mud Column	162	2345	-	-	404	5862
Inside Pressure Profile for Burst (effective at the Wellhead)						
Max. Possible Shut-in Pressure	237	3434	-	-	-	-
Full Gas Column	-	-	-	-	302	4379
Inside Pressure Profile for Collapse (effective at the Wellhead)						
Inside Partially Empty	151	2189	-	-	-	-
Inside Empty	-	-	-	-	1	15
Resulting Loads						
Resulting Load Burst	237	3434	-	-	302	4379
Burst Load incl. DF	260	3777	-	-	332	4817
Resulting Load Collapse	11	156	-	-	404	5862
Collapse Load incl. DF	11	156	-	-	404	5862

Casing Selection

Grade	**L-80**				**C-90**	
OD	**16**	in	-	in	**10 3/4**	in
Weight per Foot	**109**	lb/ft	-	lb/ft	**65,7**	lb/ft
	162,21	kg/m	-	kg/m	97,77	kg/m
ID	14,688	in	-	in	9,56	in
Coupling	-		-		-	
Burst Resistance	5740	psi	-	psi	8720	psi
(Internal Yield Pressure, psi)	396	bar	-	bar	601	bar
Burst incl. Temperature Effect	344	bar	-	bar	523	bar
Collapse Resistance	3080	psi	-	psi	6760	psi
(Collapse Resistance, psi)	212	bar	-	bar	466	bar
Yield Strength	2530	1000 lb	-	1000 lb	1198	1000 lb
(Joint Strength, 1000lb)	11253	kN	-	kN	5329	kN
Yield Str. incl. Temperature Effect	9790	kN	-	kN	4636	kN

Control Calculation Burst

Safety Factor	**1,45**	> 1.10	-	> 1.10	**1,57**	> 1.10

Control Calculation Collaps

Safety Factor	**19,71**	> 1.00	-	> 1.00	**1,15**	> 1.00

Control Calculation Axial Tension

Weight in Air	97.327	kg	-	kg	293.321	kg
Buoyancy Factor	0,869		-		0,869	
Weight in Fluid	84.557	kg	-	kg	254.834	kg
Safety Factor	**11,80**	> 1.60	-	> 1.60	**1,85**	> 1.60

4,000m Surface Located Wellbore (Target TVD: 4,000m)

Setting Depth and EMW

Section	Diameter	Depth @ Csg. Shoe		EMW @ Csg. Shoe		
		TVD	MD	Pore EMW	Mud EMW	Frac EMW
	[in]	[m]	[m]	[kg/m3]	[kg/m3]	[kg/m3]
Surface Casing	16	1900	1900	1000	1030	1739
Production Casing	10 3/4	4000	4000	1000	1030	1739

Additional Data

Parameter	Value	Unit
Steel Density	7850	kg/m3
Gas Gradient	0,02262	bar/m

Design Factors

Collapse	1,00
Burst	1,10
Tension	1,60

Calculation of the Expected Loads

Section	Surface Casing		Intermediate Casing		Production Casing	
	[bar]	[psi]	[bar]	[psi]	[bar]	[psi]
Outside Pressure Profile						
Mud Column	192	2784	-	-	404	5862
Inside Pressure Profile for Burst (effective at the Wellhead)						
Max. Possible Shut-in Pressure	281	4077	-	-	-	-
Full Gas Column	-	-	-	-	302	4379
Inside Pressure Profile for Collapse (effective at the Wellhead)						
Inside Partially Empty	181	2628	-	-	-	-
Inside Empty	-	-	-	-	1	15
Resulting Loads						
Resulting Load Burst	281	4077	-	-	302	4379
Burst Load incl. DF	309	4485	-	-	332	4817
Resulting Load Collapse	11	156	-	-	404	5862
Collapse Load incl. DF	11	156	-	-	404	5862

Casing Selection

Grade	**L-80**				**C-90**	
OD	**16**	in	-	in	**10 3/4**	in
Weight per Foot	**109**	lb/ft	-	lb/ft	**65,7**	lb/ft
	162,21	kg/m	-	kg/m	97,77	kg/m
ID	14,688	in	-	in	9,56	in
Coupling	-		-		-	
Burst Resistance (Internal Yield Pressure, psi)	5740	psi	-	psi	8720	psi
	396	bar	-	bar	601	bar
Burst incl. Temperature Effect	344	bar	-	bar	523	bar
Collapse Resistance (Collapse Resistance, psi)	3080	psi	-	psi	6760	psi
	212	bar	-	bar	466	bar
Yield Strength (Joint Strength, 1000lb)	2530	1000 lb	-	1000 lb	1198	1000 lb
	11253	kN	-	kN	5329	kN
Yield Str. incl. Temperature Effect	9790	kN	-	kN	4636	kN

Control Calculation Burst

Safety Factor	**1,22**	> 1.10	-	> 1.10	**1,57**	> 1.10

Control Calculation Collaps

Safety Factor	**19,71**	> 1.00	-	> 1.00	**1,15**	> 1.00

Control Calculation Axial Tension

Weight in Air	308.203	kg	-	kg	391.095	kg
Buoyancy Factor	0,869		-		0,869	
Weight in Fluid	267.764	kg	-	kg	339.779	kg
Safety Factor	**3,73**	> 1.60	-	> 1.60	**1,39**	> 1.60