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Risk Management and Contingency Planning for the First Icelandic Deep Drilling Project Well in Krafla, Iceland

Sebastian Homuth[1], Bjarni Palsson[2], Sveinbjörn Holmgeirsson[2], Ingo Sass[1]

[1]Technical University Darmstadt, Institute of Applied Geosciences, Department of Geothermal Science and Technology, Schnittspahnstraße 9, 64287 Darmstadt, Germany

[2]Landsvirkjun Power ehf, Háaleitisbraut 68, 103 Reykjavík, Iceland

homuth@geo.tu-darmstadt.de, bjarnip@lvp.is, sveinbjorn@lvp.is, sass@geo.tu-darmstadt.de

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ABSTRACT

The Icelandic Deep Drilling Project (IDDP) is a research program designed to evaluate improvements in the efficiency and economics of geothermal energy systems by harnessing Deep Unconventional Geothermal Resources (DUGR). The goal is to generate electricity from natural supercritical hydrous geofluids from depths of around 3.5 to 5 km and temperatures of 450-600°C. At that depth, the pressure and temperature of pure water exceed the critical point of 374.15°C and 221.2 bars, which means that only a single phase fluid exists. In order to drill into the target zone of supercritical geofluids, one of the main challenges is to deal with high temperatures and pressures during the drilling and well completion processes. Because of the great uncertainties in this project a detailed risk assessment and contingency plan is necessary.

This paper describes major geological and technical problems, in terms of drilling, in such a high temperature and pressure environment, with emphasis on the geo-engineering part of the drilling process and well completion. The natural geological risks arising from volcanic and seismic activity, as well as meeting sufficient permeable zones, are considered to be relatively minor factors when compared to the well completion process due to their low probability. The main risks are assessed in the hazard of underground pressure blowouts, meeting circulation loss zones and material failures due to the high temperature environment. In addition borehole failure, formation fracturing, cement and casing failure as well as problems during coring operations are deemed to be likely, but by applying the appropriate techniques as well as mitigation and counteractive measures, discussed in this paper, most of these risks can be reduced or prevented.

1. INTRODUCTION

The IDDP is a research program, the task of which is to evaluate improvements in the efficiency and economics of geothermal energy systems by harnessing Deep Unconventional Geothermal Resources (DUGR). The goal to generate electricity from natural, supercritical hydrous geofluids can be achieved by charging these fluids from depths around 3.5 to 5 km and temperatures of 450-600°C. The pressure and temperature of pure water in that depth exceed the critical point of 374.15°C and 221.2 bars, which means that the difference between water and steam disappears and instead of two phases only a single phase fluid exists. The IDDP target is to drill for supercritical fluid at point F, which is shown in fig. 1, separate that fluid by deep casings (~3.5 km) to prevent mixing with the two phase field of liquid and steam, and bring the fluid up to the surface as superheated steam.

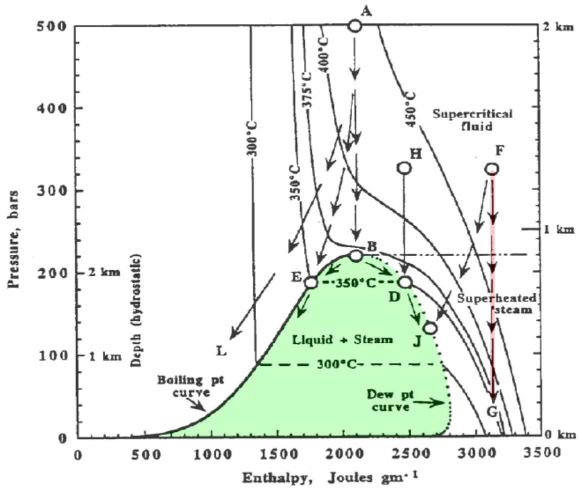

Figure 1: Pressure-Enthalpy diagram for pure water (Fournier, 1999)

For geofluids, which contain dissolved chemical components, the critical point is elevated above those values, but will be reached in greater depths with temperatures exceeding 450°C. The concept of this program is to test and prove that the production of electricity from superheated steam derived from depressurized supercritical high-enthalpy geofluids in natural settings has economical benefits over electricity production from conventional geothermal fields. Modelling indicates that under favourable conditions, a 4-5 km deep well producing supercritical fluids at temperatures significantly higher than 450°C could yield sufficient high-enthalpy steam to generate 40-50 MW_{el}. That is an order of magnitude higher electrical power output than is usual from a conventional 2 km deep well producing from a subcritical, liquid-dominated geothermal reservoir in Iceland (Fridleifsson et al., 2003).

The long-term plan of the IDDP is to drill, test and produce a series of such deep boreholes in Iceland as the Krafla, Hengill and Reykjanes high temperature geothermal systems. For the first IDDP well it is proposed to drill with the conventional rotary drilling method to complete a cased well up to 3,500 m and obtain rock samples with a spot coring program that permit a proper characterization of the mostly unknown geological conditions at greater depths than 2,400 m.

The drilling site location is in ISNET 93 coordinates: X (east) = 602607, Y (north) = 581630, Z = 553; Degrees: 65° 42.953 N, 16° 45.871 W. The well is named IDDP-1.

1.1 Drilling and Well Design for the first IDDP Well

The plan is to drill a straight vertical well to 4,500 m. The wellhead is designed for a maximum temperature of 500°C and a pressure of 19.5 MPa. Its internal surfaces will have weld overlays clad with stainless steel to withstand acid gases and erosion, because it is expected that HCl will be found in the deep section of the well. The wellhead and its valves are to be of ANSI pressure Class 2500. The well will consist of five cemented casing strings, beginning with a 32” (inches) surface casing to 90 m followed by two intermediate casing strings, the first one with 24-1/2” to 300 m and the second with 18-5/8” to 800 m. The anchor casing with 13-5/8” diameter from top to 300 m and 13-3/8” diameter will lead down to 2400 m and the production casing with a 9-5/8” diameter to 3500 m. A 7” slotted liner will be installed in the lower open hole part of the well. For all casings, thick walled API K-55 grade steel is selected; except for the top 300 m of the anchor casing string, where an API T-95 grade steel will be installed due to its better creep resistance. Hydril/Tenaris 563 couplings and threads are designated for the anchor and production casing.

All drilling works were performed by the Icelandic Drilling Company Ltd. (Jardboranir, ehf.). In June 2008 the drill rig Saga drilled for and cemented the 32" surface casing to 91 m depth. In November/December 2008 the drill rig Jötunn drilled the next two sections of the well, the 24 ½" casing to 280 m, and the 18 5/8" casing to 796 m depth. The casing and cementing job was finished on the 9th of December.

The drill rig named Tyr is scheduled for the IDDP-1 well in Krafla in March 2009 and will begin by drilling a 16 ½” well from 800 m to about 2400 m depth, followed by inserting and cementing the 13 5/8” and 13 3/8“ casing. Then a 12 ¼” drilling to 3500 m including several spot cores, and cemented casing by 9 5/8” will follow. The well will be completed by an 8 ½” rotary drilling to 4500 m depth, including several spot cores. The drilling for the 13 3/8” casing to 2400 m is currently (May 2009) in progress. Further drilling works are planned as stated below:

June 2009: Drilling for 9 5/8" casing to 3500 m – including ~ 2 spot core

June-July 2009: Drilling with 8 ½" drill bit to 4500 m - including ~ 8 spot cores

Autumn 2009: Flow Test

The estimated drilling costs for the first well are approximately $20 million US.

2. RISK ASSESSMENT AND EVALUATION

A risk analysis is defined in the ISO definition (ISO, 2002) as the ‘systematic use of information to identify sources and assign risk values’. The risk assessment therefore has to focus on the identification of applicable hazards and its description (including quantification) of applicable risks to the process, personnel, environment and assets.

In order to do so, a broad basis of geological, technical and well design data had to be analysed. Within these data also lays the limitation of this risk analysis. There has to be a sufficiently broad basis of relevant data for the quantification of failure frequency or failure causes, which is not always given, especially in mostly unknown geological formations with the present of supercritical geofluid. The data used usually refers to distinct phases and operations, and therefore the results can only be used to a certain extend or should not be used for other phases and operations. Assumptions and premises are stated in every chapter, where it was necessary to do so.

3. GEOLOGICAL SETTING OF THE KRAFLA AREA

The high temperature geothermal system of Krafla was chosen as the first drill site for the IDDP project based on intensive geophysical and geological exploration. The geothermal field of Krafla is located in the north-eastern part of Iceland within the Krafla Central Volcano complex. The geology of this area is dominated by the presence of the Krafla central volcano, which features a caldera and an active NNE trending fissure swarm crossing the caldera. About 100.000 years ago, at the end of the last interglacial, a large (some km^3), explosive eruption of intermediate to acidic composition resulted in the formation of the Krafla caldera, which has dimensions of 8 by 10 km. During the last glacial period the caldera was more or less filled with volcanic material, and subsided some hundred meters. At the same time the fissure swarm crossing the center widened by some tenths of meters every 10 thousand years, resulting in the elliptical shape of the caldera (Saemundsson 1991).

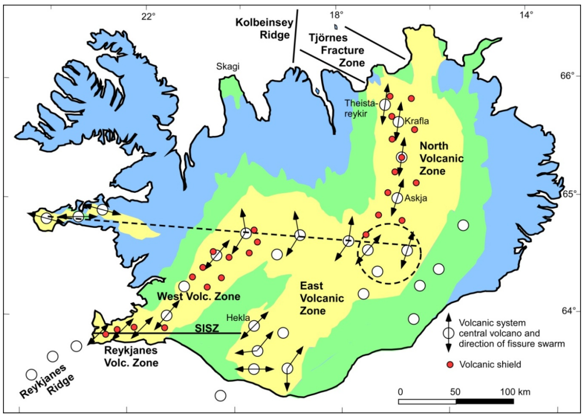

Figure 2: Simplified geological map of Iceland. Yellow area: volcano-tectonic zone younger than 0.8 Ma, green area: bedrock 0.8-3.3 Ma old, blue area: Tertiary bedrock with age up to 16 Ma. Open circles: central volcanoes, arrows: direction of the associated fissure swarms, filled red circles: large olivine-tholeiite lava shields. Heavy or dotted lines: transform faults. Dotted circle: proposed location of the mantle plume beneath the island. SISZ: South Iceland Seismic Zone. The map is modified from Saemundsson, 1978

Some major lithological units have been identified, including two hyaloclastite units reaching to depths of 800–1000 m separated by basaltic lavas, underlain by a lava succession to 1100–1400 m depth, which sometimes has thick hyaloclastite interbeds. Small basaltic and dolerite intrusions forming dykes and sills are common in the lava succession. Below 1100 and 1400 m depth they dominate the succession. Below 1800 m the small intrusions are replaced by larger intrusive bodies of gabbros and occasional granophyres. The intrusive rock intensity is 80–100 % below 1500 m in most sections of the Krafla field, and involves both gabbros, and coarse grained acid rocks (granophyres) (Fridleifsson et al., 2006).

The heat source for this geothermal system is a well determined magma chamber, which was identified with S-wave attenuation at relatively shallow depths between 3 to 8 km during the 1975-1984 volcanic activity (Einarsson, 1978), which is known as the “Krafla Fires“. This last eruptive period resulted in 21 tectonic events and 9 explosive eruptions (Einarsson, 1991). The hypothesis of a solidifying magma chamber under the Krafla volcano inferred from the measurements by Einarsson are confirmed by accumulated well field data on gas emissions and temperature distributions.

3.1 Structure of Krafla Area

The fissure swarm that intersects the Krafla caldera, which was formed about 100 thousand years ago, is 5–8 km wide and about 100 km long. Two other fracture systems have been identified in the Krafla area. The caldera rim reveals curved tectonic. The Hvitholar drilling field is where the caldera rim and the NNE trending fissures cross. WNW–ESE trending fissures are exposed in the Sudurhlidar wellfield and have been related to intrusive activity into the roots of the central volcano (Arnason et al., 1984).

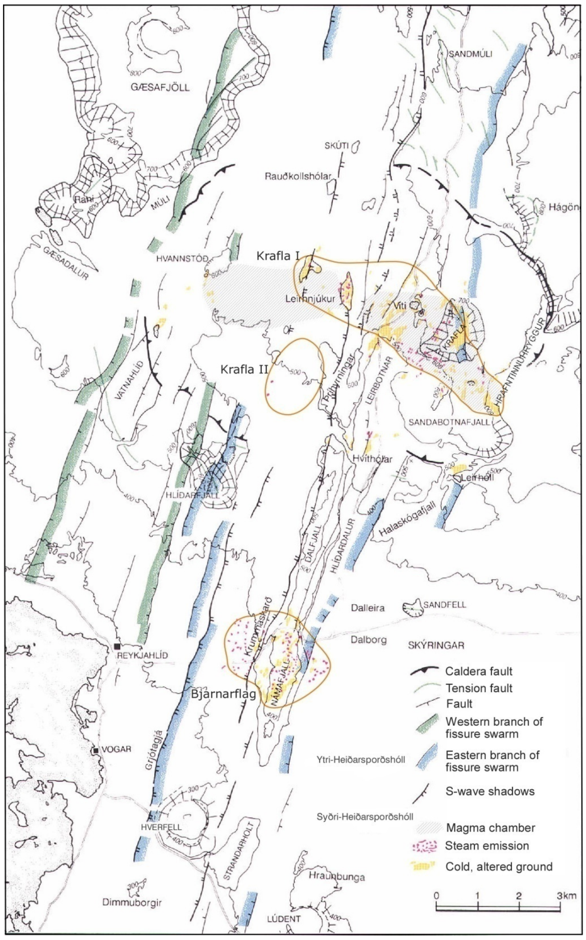

Figure 3: Central part of the Krafla volcanic system showing the caldera and the fissure swarm which traverses it (Saemundsson, 1991)

The volcanic active zone crosses the caldera at the divergent plate boundaries where Leirhnjukur is in the center. During the Krafla fires large scale faulting extended north and south from Leirhnjúkur and intersected volcanic eruption sites. Early in the volcanic period a NNW-SSE trending normal fault displaced the south slope of Mt. Krafla as well as fumaroles became active on it.

Geothermal manifestations are mainly concentrated on the western and southern slopes of Mt. Krafla and at Leirhnjúkur in the center of the caldera. The activity is manifested in the form of mud pools and fumaroles with minor sulphur deposition. Most of these manifestations are fault controlled, but some of the larger fumaroles are associated with explosion craters. At Leirhnjúkur, in the center of the caldera, the fumaroles and mud pools follow the trace of closely spaced eruptive fissures, among them the two youngest ones, which erupted during the Mývatn and Krafla fires 280 and 30 years ago (Björnsson et al., 2007). During both volcanic episodes the geothermal surface activity increased significantly. Minor surface manifestations occur at the southeast margin of the caldera.

4. GEOLOGICAL RISKS

In this chapter the major geological risks, like hazards from volcanic eruptions and earthquake activity and meeting sufficient permeable zones, are discussed. Because of the close relationship between volcanic euptions and ground movements the risk assessment for both seismic active processes is summarized in chapter 4.2.

Due to the complex chemical rock-geofluid interaction and the limited geochemical data concerning supercritical fluids from high temperature and high pressure geothermal fields, the assessment of the influences of those fluids on the drilling operation and resulting hazards would go beyond the scope of this drilling risk assessment and is therefore not discussed here. But it shall be noted that the chemical composition of the geofluid and its acidic nature is one of the major concerns to the IDDP-1 well completion especially in terms of the long term operation of the well.

4.1 Volcanic Hazards

To quantify volcanic hazards a study of the eruption history and past events of a dormant volcano can give a good estimate of the long-term probability of renewed activity. The rifting events which took place at Krafla from 1975-1984 and subsequent volcano inflation until 1989 have been followed by no eruptive activity in the area. No known magma accumulation is taking place at a shallow depth in the crust, but magma accumulation near the crust-mantle boundary has been suggested, or alternatively that signal may relate to post-rifting adjustments (Björnsson et al., 2007). Geodetic measurements indicate a relatively uniform strain accumulation along the length of the plate boundary in north Iceland and suggest that the Askja segment adjacent southward to Krafla should be considered as the likely location of renewed activity. Inferred from the last eruptive events, the eruptive phases of the Krafla vulcano are episodic and occur at 250-1000 year intervals, while each eruptive phase apparently lasts 10-20 years.

Based on the minimum recurrence intervals of about 250 years in earlier episodes, and the fact that it takes time to build up sufficient tensional stress for a new episode, the Krafla system is considered comparatively safe for utilization during this century at least. It stands to reason that existing wells, as well as production wells, may be affected by ground movements. Partial collapse that may block the wells is a possibility, but seismic action is not known to have severely damaged production wells in Iceland, except on one occasion when a fracture passed through a well in Bjarnarflag during the Krafla fires. It is also known that volcanic action did damage wells located inside the central graben during the Krafla fires.

Ash-fall from distal volcanoes cannot be excluded as a potential hazard, however large plinian eruptions are rare. Phreatic eruptions from sub-glacial eruptions are more common in Iceland, but only a few have caused heavy ash-fall in NE-Iceland.

In terms of hazardous floods caused by volcanic eruptions, the geothermal areas of the NVZ are out of reach of catastrophic floods due to the volcanic melting of glacier ice.

4.2 Earthquake Hazard

The biggest tectonic earthquakes in and around Iceland occur in the transverse zones in south (SISZ) and north Iceland and may reach at least magnitude seven. In northeast Iceland earthquakes occur mainly within the Tjörnes Fracture Zone. In the spreading volcanic zones magnitudes are smaller and usually do not exceed 5. This is due to the fact that the elastic crust is presumably only 5-10 km thick in the volcanic rift zones and the temperature gradient is high. In the transform zones (TFZ and SISZ) the elastic crust is thicker, some 10-15 km, and the temperature gradient lower. Volcanic earthquakes located in the vicinity of the major volcanoes usually do not exceed magnitudes 4-5. Small earthquakes, which occur quite frequently in high-temperature geothermal areas, usually do not exceed magnitude three.

In northern Iceland, the SIL seismic monitoring system has been in operation since 1994 (Stefánsson et al., 1993). During this period, seismic activity within the region has remained low, with the largest earthquake registering 2.6 on the Richter scale. A complete catalogue exists for earthquakes exceeding magnitude 1.2. Within the period of the operation of the SIL seismic network 116 events with a magnitude above 1.2 have been detected in the area; yielding a b-value of 1.21 ± 0.22. The b-value is the relation between earthquake size and the frequency of occurrence, which is represented by:

$$\log N = a - b \cdot M \qquad [1]$$

where N is the number of earthquakes ≥ M. The maximum likelihood estimate of b (for 95% confidence) is

$$b = \frac{0.4343}{(M_m - M_{min})} \pm \frac{1.96b}{\sqrt{n}} \qquad [2]$$

were M_m is the mean magnitude for all events with magnitudes above or equal M_{min}, and n is the number of events (Aki, 1965).

Earthquake hazards are commonly estimated using b-values. The estimation is based on the assumption that the value is stable, but many studies have demonstrated variations in the b-value over time. In the vicinity of Krafla, a significant change between the periods before and after 1975, from b ≈ 0.9 ± 0.2 to b ≈ 1.2 ± 0.2 could be observed. A weak crust that is incapable of sustaining high strain and heterogeneous stresses could be a plausible explanation for the higher b-values after the 1975 event. The lower b-value before the last rifting episode indicates that the crust has stabilized during the 200 years since the 1724 – 1746 rifting episode (Björnsson et al., 2007). Therefore, in the following decades, a b-value of 1.0 is a conservative value for a hazard estimation in the area. Consequently, the probability of a magnitude 5 earthquake is considered to be low. The probability for such an event happening, especially during the drilling operation, is assessed as a minor risk with a probability of occurrence less than 20 %.

In general it is concluded, that a rifting episode in the NVZ as a whole can be expected roughly once every century and in the case of Krafla the rifting episodes may be accompanied by a volcanic eruption. Deformations are expected at Krafla during such inter-rifting periods. Local magmatic and geothermal pressure sources are known to have contributed continuously to deformation processes at Krafla in the past decades. Deformation due to pressure variations in the shallow magma chamber at the Krafla volcanic system may be expected, as well as deformation due to exploitation and other processes in the geothermal fields. They can cause deformation at a rate of up to the maximum of a few centimeters per year (Björnsson et al., 2007).

A volcanic eruption as well as a major earthquake (Magnitude considerably above 3) can cause severe damage to the drilling rig, the working crew and of course the wellbore. On that account the impact of both the geological risks on the drilling process and well completion is considered to be very significant. Possible consequences are ash deposits, mast collapse, water and electricity supply failure, access difficulties, fires on the drilling rig, engine failures, blowouts and wellbore collapse. Both geological risks are assessed with a high impact factor. In terms of volcanic hazards the factor is 5, in terms of earthquake hazards the factor is assessed at 4.

Due to the fact that there are no measures to prevent an earthquake or volcanic eruption it is important to observe and monitor the seismic activity not only in the Krafla region but also in other volcanic vicinities in the catchment area of Krafla. This is done by a seismic monitoring system with geophones distributed all over Iceland.

4.3 Permeability

Numerical simulation studies of the generating capacity of the geothermal reservoir in Krafla, described by Bödvarsson et al. (1984), reveal that the average transmissivity is low. The Krafla model comprised a vertical cross section which included both Leirbotnar and Sudurlidar well fields. The simulation model is in agreement with the assumption that the reservoir system is controlled by two upflow zones: one at Hveragil and the other very close to the eastern border of Sudurhlidar. The lower reservoirs in Leirbotnar and Sudurhlidar are two phase, with average vapour saturation of 10-20% in the fracture system. The porosity of the reservoir was assumed to be 7%. The permeability of the reservoir was about 1-4 milli Darcy (mD) with an average of 2.0 mD (= $1.97 \cdot 10^{-15}$ m^2). The values for this transmissivity were obtained from detailed analysis of injection tests. The permeability seems to be controlled by vertical fractures rather than by horizontal zones. The best match with well flow data was obtained when assuming high vertical permeability.

Circulation loss zones are perhaps the best indicators of permeability. These zones commonly appear as localized lows in temperature logs – a phenomenon reflecting slow thermal recovery following invasion by cool drilling fluids. Where a fracture coincides with such a low temperature it is assumed to be permeable. Injection tests in well KG-25, which is located in the close vicinity of the IDDP-1 well, showed that the correlation between the measurements and the used model was very close. Gudmundsson et al. (2008) estimated the transmissivity to $3.2 \cdot 10^{-8}$ m^3/Pas, the formation storage $8.8 \cdot 10^{-8}$ m/Pa and the skin effect +0.2 (). Compared to other wells in the Krafla area the transmissivity of well KG-25 is above average.

The risk of not meeting a sufficient permeability increases with greater depth due to the higher litho static pressure, which favours the closure of existing fractures. But on the other hand the increased transmissivity in the Vitismor well field and the experience with other ultra deep geothermal wells like the WD-1 well in Japan showed that permeable horizons can occur in great depth, as long as the brittle-plastic boundary of the basalt rock is not reached. Investigations on the WD-1 well demonstrated that the brittle-plastic boundary constrains the maximum depth of fracturing. The results from the a recent magneto-telluric (MT) study by Arnason et al. (2008) allow the presumption that the beginning of the brittle-ductile transition zone is located somewhere in the depth range of 4-5 km, which is the target area of the IDDP-1 well. That leads to the conclusion that the probability of not meeting a sufficient permeable horizon in depths below 4000 m is assessed to be 50%.

If no sufficient permeable horizon intersects with the drill path and no charging of supercritical fluids is possible, the whole project is put at risk, unless cost-intensive side tracking is not considered. Consequently the impact factor is assessed to 4. To have further options at that point in the project it is necessary to investigate possible upper feed zones while drilling, before sealing them out, in case it is necessary to penetrate the casing at that depth interval again. It might also be worthwhile to think about possible reservoir enhancement methods like hydraulic fracturing.

5. DRILLING RISKS

Drilling is one of the areas in which geothermal resource development has benefitted considerably from the expertise of the oil and gas industry. Drilling for geothermal energy is quite similar to drilling for oil and gas. But there are some key differences due to the high temperatures associated with geothermal wells, which affect the circulation system and the cementing procedures as well as the design of the drill string and casing.

To assess the risks of drilling due to supercritical geofluids, the effects of drilling activities on the temperature–pressure conditions in the well-adjacent formations and inside the well must be combined with behaviour models of supercritical geofluid capable of predicting when supercritical conditions occur. Since some of these behaviour models of supercritical phases are currently not well established and/or efforts of current research, these models and pressure–temperature simulations require knowledge about input parameters that are associated with considerable uncertainty. Also the long term consequences on materials of being exposed to supercritical geofluids are unknown. These preconditions have to be considered while reading the following chapters.

5.1 High Temperature and Pressure Environment

To estimate the pressure and temperature (P-T) conditions in the IDDP-1 well it makes sense to have a look at well data from nearby wells and wells which reach the deepest depths in the high temperature geothermal field of Krafla. The temperature increases with depth and follows what is referred to as the "boiling-point depth curve" (BPD). Therefore we can use the P-T data from the nearby wells KG-25, KG-04 and KG-10 as a guide to infer that in the IDDP well, conditions should follow the BPD-curve until the critical point is reached at about 3.5 km depth (fig. 4). It is planned to cement the casing at approximately 3.5 km depth. Thus supercritical rock temperatures and pressures should be reached soon after drilling below the casing. But also the possibility of conditions exceeding the BPD-curve at a shallower depth needs to be considered. This could be a likely scenario, which already occurred in well NJ-11 at Nesjavellir in 1985, where the temperatures below 2200 m certainly surpassed the conditions determined by the BPD-curve, and involved superheated steam at least hotter than 380°C, if not supercritical conditions as suggested by Steingrímsson, et al. (1990). This scenario is illustrated in fig. 5 where the temperature-depth profile shows a borehole intersection with a permeable structure close to a heat source, penetrating the contact aureole of a subvertical gabbro intrusion. The design of the IDDP drillhole should be capable of handling such conditions of superheated steam, with the anchor casing cemented to 2.4 km depth.

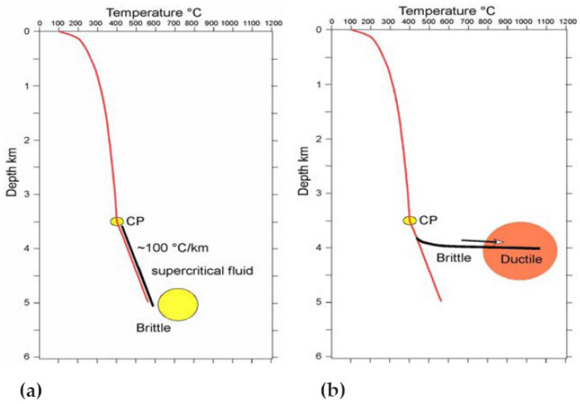

Figure 4: Possible temperature scenarios for the IDDP-1 well around a cooling intrusion at Mt. Krafla. (a): along a margin, (b): into the top of the magma chamber at app. 4 km depth (Fridleifsson et al., 2003)

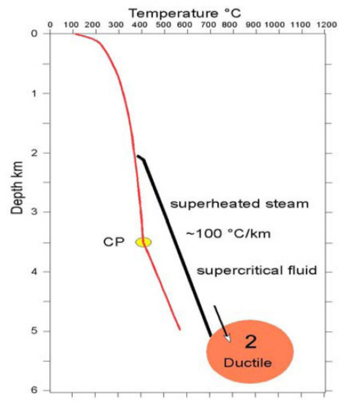

Figure 5: Scenario: Drillhole penetrating the contact aureole to subvertical gabbro along the vertical margin of a cooling intrusion, involving upward flow of superheated steam derived from supercritical fluid (Fridleifsson et al., 2006)

In 2008 critical conditions were found in well KJ-39, which is an inclined 2800 m deep well located southwards of the IDDP drill site with a measured maximum temperature of 386°C in ca. 2400 m depth. In this case it was actually drilled into magma. The drill bit showed after recovery to the surface adhesion of fresh formed glassy basalt. Geophysical measurements in the vicinity of well KJ-39 showed no indication of elevated magma in this area which illustrates again the great uncertainties in this project. Therefore during the drilling and completion process of the IDDP-1 well at the Vitismor field, one should be prepared for P-T conditions surpassing the BPD-curve. However, in the case of borehole KJ-39, the drilling crew was able to control the well and set a cement plug, which shows that even those critical conditions can be handled.

Different MT-studies, with respect to the IDDP drill site and the Krafla drill field, showed, that the MT-data supports the conclusion of the presence of a shallow level magma chamber below the Krafla drill field. However, the depth of a molten chamber cannot be determined exactly, as there is an uncertainty as to how the low resistivity in detail should be interpreted. But a partial melt and/or brittle/ductile boundary at subsolidus temperatures might result in lowering the resistivity at depths, and results of drilling just above the resistivity peaks closest to the Viti crater do not suggest that molten rocks exist just below the depths penetrated by drilling so far (Friedleifsson et al., 2008). The overall shape of the top of the low resistivity zone can be interpreted as an indicator of proximity to a magma chamber. In this respect a 5 km deep well at the IDDP-1 drill site would be in contact with the low resistivity surface as presented by Árnason et al. (2008). The boundary of recorded earthquake activity is another indicator for the partial melt or brittle/ductile zone at that depth. Therefore it can be assumed that temperatures in that depth range are around 600°C.

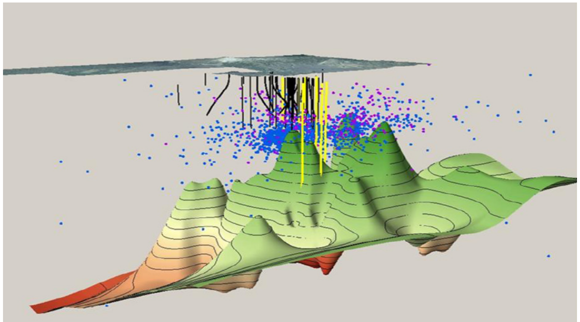

Figure 6: Earthquakes recorded from 2004-2005 in violet and from 2006-2007 in blue, View from NE (Fridleifsson et al., 2008)

5.1.1 Temperature Limitations and Counteractive Measures

The borehole temperature is an important parameter in relation to the drill tools and the maximum temperature ratings of the drilling mud. The following conventional methods were used to estimate the well temperature in the WD-1 well in Kakkonda, Japan, and can be applied as well to the IDDP-1 well: Mud temperature monitoring in and out of the hole; Thermometers can be installed on top of survey tools so that borehole temperatures can be monitored at less than one hour recovery time; Measurement-while-drilling (MWD) temperature surveys; mud-circulation temperatures in the hole can be monitored when the MWD tool is used for drilling. Tests showed that temperatures inside and outside the tool equalized within a few minutes (Saito, et al., 1998).

To measure the undisturbed formation temperature down hole, temperature melting tablets can be used, as it was done in the WD-1 well in Kakkonda, Japan, to confirm the high temperature region, which could not be measured by available PTS and Kuster tools. Muraoka et al. (1998) used tablets for temperature measurements with twelve different melting points at temperatures ranging from 399 to 550°C. The tablets were made of various inorganic compounds such as chromium, molybdenum, tungsten, barium, sodium and potassium. Each tablet was packed in a stainless steel container and installed in a steel vessel that was held at the bottom of the well for one hour using a stainless steel wireline. After removing the tablets from the borehole, the different tablets were checked to see whether they had melted or not in order to infer approximate bottom hole temperatures.

But other solutions for temperature measurements up to 550°C are available: namely, the slick-line computer tools and the Distributed optical-fiber Temperature Sensing (DTS) system. The slick-line tools employ a self-contained, battery-powered computer and temperature sensor housed in a Dewar flask assembly, which is lowered into the well on a solid wire. The Dewar flask protects the sensor under high-temperature environments inside the well and has been tested up to temperatures of 400°C continuously for about 10 h. Another solution, the DTS tool, developed by Hurtig et al. (1994), has the potential of withstanding well temperatures of up to 550°C. The tool works using Raman Effect backscattered laser light in an optical fiber. Observations of the intensity of backscattered light with time can be used for determining the temperature along the entire length of the optical-fiber cable instantaneously. Although this tool is less accurate in temperature and depth by an order of magnitude relative to the electric-line and computer-based slick-line tools, it can be gainfully employed to monitor transient events in a well by keeping the entire cable lowered inside the well for several days without perturbing the water column due to repeated lowering and raising of the tool.

One of the most important functions of the drilling fluid is to cool the bit and well. The temperature downhole influences bit life and dictates what downhole tools can be used. Tools such as mud motors, drilling jars, logging tools and measuring-while-drilling devices (MWD) can be deployed. Most commonly used in geothermal drilling are roller cone bits with hardened-steel teeth or tungsten-carbide inserts. Since the steel used in roller cone bits is drawn at temperatures 200–250°C, these bits lose much of their strength when operated at temperatures in excess of 250°C. This causes rapid failure of bearings and steel teeth as well as loss of inserts with the insert bits. Expensive roller cone bits are provided with sealed lubrication systems, which have rotating rubber seals to hold the grease in the bearings. But these rubber seals also have a temperature limitation of about 200°C. Improved seals and improved high-temperature lubricants are required in high-temperature geothermal drilling. Diamond drills can drill at temperatures in excess of 500°C. However, since their drilling rate is much slower compared to roller cone bits, they do not provide a very acceptable solution to the problem of high-temperature drilling. Three-cone bits have temperature sensitive parts such as O-ring seals and diaphragms, which are prone to damage during drilling in high temperature geothermal wells. O-ring seals never survived more than 29 hours of rotating time in other wells where the formation temperature is over 350°C (Saito, 1996). Other temperature sensitive parts are the stator of the mud motors and the electrical components in the logging tools. As long as the mud or water circulation is maintained, it is even possible with conventional geothermal drilling methods to keep the downhole temperature below 100°C.

To avoid mud gelation in the high temperature borehole very thin high temperature drilling mud can be used, even though this compromises the cuttings-cleaning efficiency. This mud consists of 3% bentonite, 0.1% high temperature dispersant, 1% lubricant, and caustic soda. The specific gravity yield value and plastic viscosity of the mud is then in between 1.1 to 3 lb/100ft^2 and 4 cP, respectively.

Conventional mud coolers can be used to cool the return mud.

A variety of commercially available high temperature downhole tools like rated positive displacement motors and retrievable-type measurement-while-drilling tools, which are partly still under development (Hiti-Project) can be applied. Those tools can be set by wireline after the well has been cooled by circulating the mud at the bottom of the well.

Experiments in the exploration well WD-1 in Kakkonda, Japan, showed that a geothermal well can be drilled even where the formation temperature is as high as 500°C, provided the well is properly cooled and conditioned to permit drilling with conventional methods. But it becomes very complex to continue drilling operations in the presence of multiple difficulties such as high temperatures and gas ejection. The key to overcoming the high temperature environment is the mud cooling system, which cools the return mud and a top drive system, which in turn cools the bottom hole assembly continuously while running every drillpipe stand into the hole. With these cooling methods, available positive displacement motor and measurement-while-drilling tools could survive in such a high temperature environment. Saito et al. (1998) showed that the O-ring seals of the three-cone bits could survive for more than 60 rotating hours and could drill more than a 100 m section, even where the static formation temperature was over 350°C. So the cooling depends highly on the rate of circulation (l/s), the borehole diameter and whether there are loss zones or not. This is especially important in terms of coring.

By reaching depths with temperatures above 300°C the probability of temperature related effects on material and well control becomes quite likely. That is why the probability of material failures including the drill bit, mud motors and drill string assessed to 65-75%. In terms of temperature effects on logging tools the risk is assessed to 40%. The reduced risk in terms of logging devices can be explained by the newest developments in the insulation of these devices and developed procedures as they are stated above. The risk of fracturing the formation due to cooling effects is assessed to 50% due to the fact that basaltic rocks in general are more resistant to thermal stress than metals. In terms of formation fracturing caused by high fluid column and/or mud pressure the probability is expected to be 60%.

The impact of high temperatures and pressures on the drilling process will primarily result in poor bit performance and therefore in low penetration rates, which will delay the whole drilling operation, which again will result in an increase of the drilling costs. The high temperature environment is also problematic for the drill string and casing material whether in alleviated form or not. The Icelandic drilling crews have some experience with high temperature wells up to 380°C, but temperatures above this level have not been experienced in active drilling processes. Based on the local expertise and the experience from the high temperature well in Kakkanoda, Japan, a risk in material failure cannot be excluded and is quite likely in the very high temperature environment at the bottom of the planned borehole. Thus the impact factor is assessed to 3, if mitigation and action measures cannot be applied or fail.

5.2 Underground Pressure Blowout

There is always the risk of a blowout while drilling in a geothermal field. A blowout may occur when an unexpected, high-pressure permeable zone is encountered. An underground pressure blowout can be defined as an uncontrolled flow of geofluids from an underground reservoir through the wellbore and into the atmosphere or another underground formation. Deep wells with high temperature and high pressure, drill locations in volcanic active areas, and geofluids in supercritical phase are some of the challenges that characterize the first IDDP well in Krafla. All of these aspects are associated with an increasing blowout risk.

The use of blowout preventers is standard practice nowadays. These are a set of fast-acting valves attached to the casing being drilled through. In the event of a “kick” from the well, these valves are slammed tight around the drill string, effectively closing off the well. Another valve attached to the wellhead just above the casing allows for controlled venting of the well to a silencer until the well is brought under control, usually by quenching the well with cold water.

The first steps towards blowout control have to be established in the planning phase of a new exploratory well. Well known deterministic coherences and drilling experience form the basis for the development of drilling procedures, casing programs and mud programs. The actual value of the most important parameters included in the well planning process is, however, uncertain, e.g. pore pressure and formation strength. Thus, the potential to manage the parameters that are decisive to the outcome of the drilling operation depends on good predictions in the well planning phase and the ability to organise personnel, to establish procedures and equip the drilling rig.

Due to the lack of experience with supercritical fluids and the limitations of the available data one could only make general conclusions. Therefore it is recommended to be prepared for the worst case. That means, in particular, having backup cooling systems, replacement equipment, and an additional blowout preventer (BOP) on the drill site to be able to act quickly in case of emergency.

Several common kill methods like the so called “running kill method” or “bullheading” and others can be applied in case of such an incident. If these efforts should fail, the drill pipe can be cut with the shear rams and the drill string allowed to fall to the bottom, and at the same time close the well. By having the tool joint in the proper place the drill string can be held by the pipe rams, preventing the string to fall to bottom (Thorhallsson et al., 2003) It should be noted that all operations, such as cutting the drill pipe or pumping cement into the hole for a permanent seal are examples of last resorts.

The risk of having an underground pressure blowout is dramatically increased in a very high pressure and temperature environment like it is in the target area of the IDDP-1 well. The probability is therefore assessed to 90%. If the cooling of the drilling fluid is not sufficient or the described mitigation and counteractive measures fail, a loss of drill pipe pressure with changes in annular pressure, the loss of large volumes of drilling fluid, or the total loss of drilling fluid returns will cause an underground blowout. Blowouts are the most spectacular, expensive, and feared operational hazards in the whole drilling process. Thus, they may result in costly delays in the drilling program, may cause casualties, serious property damage, and pollution. That is why the risk impact factor is determined to be 5.

5.3 Circulation Losses

Lost circulation can take place in naturally occurring fractured, cavernous, sub-normally pressured or pressure depleted formations. Induced losses can occur from mechanical fracturing due to pressure surges while breaking circulation. In all cases of lost circulation, measures should be taken to keep the hole full. The borehole can be filled with either light drilling fluid or water. A loss of fluid returns will lower the hydrostatic head of the drilling fluid in the wellbore, thereby possibly inducing a kick. The influx fluid will then flow to the surface or into the zone of lower pressure. Loss of returns while trying to kill a kick can develop in an underground blowout. In case a kick is impending or an underground blowout has started, a barite plug may be effective in isolating the thief zone from the kick. In addition, fine sealing material may be used to control slow losses instead of coarse materials that may plug the bit and choke valve or choke. Occasionally, a coarse sealing fluid may be used when bullheading down the annulus. Afterwards, the lost circulation zone should be sealed once the loss zone has been isolated from the influx zone.

On the other hand, if the drillhole intercepts a major permeable fracture zone at depths between 2.4–3.5 km, and that fracture zone produces superheated steam, every effort should be made to study it thoroughly before casing it off. Even though such additional activities would delay the completion of the drillhole and increase its costs, ignoring such an opportunity could risk the success of the project, as there would be no guarantee that another major permeable zone would be found at a greater depth (Fridleifsson et al., 2003).

Circulation losses can be expected at all depths of the IDDP-1 well, but mostly one would expect relatively narrow fractures at intrusive rock contacts within the complex. Most of such fractures have already sealed by mineral precipitates, and will probably not be detected during drilling. Only fracture permeability is expected. Most loss zones are expected to be small due to secondary minerals, but some fracture can be quite open, especially near young subvertical dikes. In general the nature of loss zones at temperatures above 400°C is unknown. Gas content at high temperatures could be quite high and could mix with the drill fluid and expand upon a decrease in pressure.

The many fractures and associated circulation loss zones in the shallow part of the IDDP-1 well and the predicted deeper permeable zones in the reservoir have been formed by recent and modern stresses. Those trends are also likely to occur at greater depths. Fracture densities from core observations of other geothermal drilling projects show similarities between shallow and deep reservoirs in terms of fracture distribution. Although the deep reservoirs, due to the higher litho-static pressure are less permeable, the fracture density is not necessarily lower (Muraoka et al., 1998). Also, the great difference of temperatures in the two reservoirs seems to be independent of fracture density. Therefore the risk of meeting severe circulation loss zones (losses of drilling fluid exceeding more than 20 l/s) is high at all depth intervals and assessed to be 80%.

Loosing greater amounts of drilling fluid through fractured zones can lead to getting the bottomhole assembly stuck and loosing the ability to cool the drilling equipment sufficiently. This can cause severe damages to the drilling equipment and casing string and is therefore assessed with an impact factor of 4.

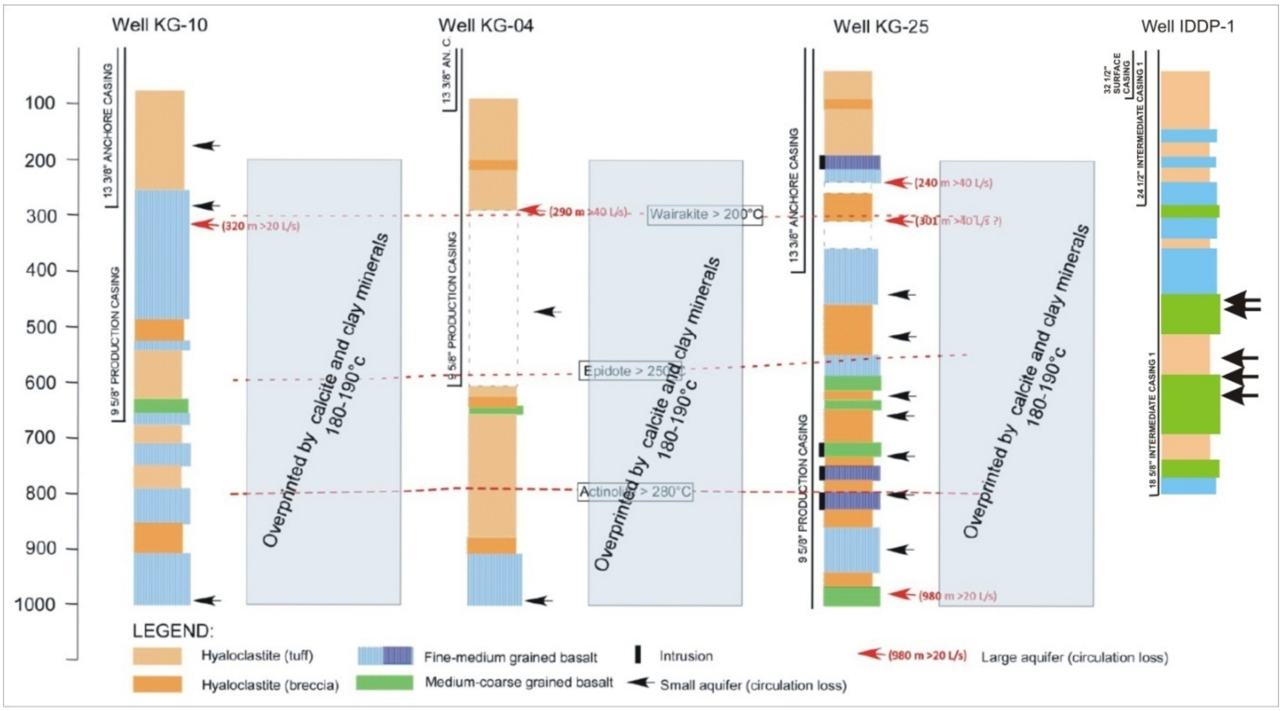

Figure 7: Profiles of wells KG-10, KG-4, KG25 and IDDP-1 (13.12.2008) with lithology, casing program and circulation loss zones (Palsson et al., 2008, modified)

5.4 Coring

Different drilling options and well designs were evaluated in the planning phase in order to get as much coring done as possible, but mainly for financial and technical reasons a spot coring program for the final section between 3400 – 4500 m was favoured over a continuous coring below 2400 m depth with a hybrid coring system. Because of the reduced space in the borehole due to the standard coring assembly, the circulation rate is reduced down to a seventh of the median circulation rate during conventional drilling. Results obtained by Huang (2000) by modelling with the STAR program showed that a conventional well drilled with an 8-1/2" bit and water could be cooled to at least half the bottom hole temperature, whereas a cored hole receives almost no cooling due to the small circulation rates of 3-5 l/s during such drilling (Thorhallsson et al, 2003).

The actual plan is now to drill spot cores anticipated from both the expected transition zone to supercritical from 2400-3500 m depth, and from within the supercritical zone itself between 3500-4500 m. The final section from 3400 – 4500 m is drilled as a 8 ½" hole. The spot cores will be taken with a new developed coring barrel.

In November 2008 a successful trial spot coring test was performed at 2800 m depth in the production well RN-17 B at Reykjanes. The core test was performed in an open hole at 35° inclination with newly built coring equipment. The main benefit of the core barrel is its unique feature to enable much greater water flow-rates for cooling during coring, up to 40 l/s, as compared to conventional core barrels with only 3-5 l/s flow rates (Fridleifsson and Thorhallsson, 2008). The core recovery rate was nearly 100% and only minor improvements on the existing drilling equipment is needed before further spot coring in the IDDP-1 well in Krafla can take place. For blowout protection, a check valve is built into the top of the barrel sub. The core bit is of a diamond impregnated type, with large cut-outs for assuring a high circulation flow. The core bit experienced some 280°C during test coring, and the entire operation took ca. 33 hours rig time for a 9.3 m coring track (Thorhallsson, 2008).

The risk of getting stuck in the hole or significantly damaging the coring equipment downhole due to the high temperature environment is severely reduced by running higher circulation rates during coring. But the risk also increases by meeting circulation loss zones or weak formations. In both cases a loss of circulation fluid could lead to total failure of the coring procedure. The risk of meeting weak formations in greater depths is due to the pressure environment, and is almost negligible, but the risk of losing too much drilling fluid during coring in a feed zone is assessed as likely and therefore was assessed to be 60-75%. At least in the upper 2100 m those possible feed zones can be inferred from the surrounding wells (see chapter 5.3).

Different impacts on the IDDP have to be considered in terms of coring operations. If the rate of penetration while coring is too low over a longer time frame, which means that the benefit/cost ratio is no longer justifiable, the coring operation might have to be stopped. In case it is not possible to maintain a sufficient drilling fluid circulation and the risk of an underground pressure blowout increases, even with the advanced coring system described above, the coring operation has to be stopped immediately in order to prevent bit burning, insufficient borehole cleaning and kick hazard. In both cases the impact on the drilling process is rather small and therefore assessed with an impact factor of 1. However the loss of scientific opportunities by the lack of core investigation might be rather significant, but that is not subject of this assessment.

5.5 Borehole Failure

There are several factors which control the condition of the wellbore. There are mechanical influences related to damaging and removing the rock caused by the drill bit, stabilizers, and drilling fluids used during the well construction. These parameters control the initial geometry of the wellbore, and while they can cause some rugosity, they rarely lead to total wellbore failure. The state of stress around the wellbore after bit penetration is another matter. The wellbore state of stress is a function of the initial earth stresses prior to penetration, the wellbore geometry, the rock properties, and the current pressure inside the wellbore imposed by the drilling fluid.

Wellbore stress generated by annular pressure (or drilling mud) controls the opposite condition. In case the wellbore pressure becomes too high, either leakage of annular fluid into pre-existing fractures or tensile failure of the rock resulting in a hydraulic fracture will occur. While this may be highly desirable as an intentional form of reservoir stimulation, it is not so in the upper parts of the wellbore and should be avoided.

In geomechanical terms the wellbore failure is defined by wellbore breakouts, which means that parts of the borehole wall cave in due to stress concentrations at the wall itself that result in shear failure. The width of the breakout depends on stress conditions, rock properties and drilling fluid pressure. If the breakout width exceeds approximately 90° to 100°, it is highly likely that the rest of the borehole wall will collapse (washout). Consequently, if the stress and mud conditions are right, tensile cracks can be created at the points along the wall that are in tension.

Due to the lack of data in terms of rock properties and stress field analysis, the assessment of wellbore failure can only be based on regional fault and fracture models existing in literature. As was inferred from the regional geological maps, the main fault direction is NE-SW with minor fissure swarms stretching SSW to NNE, which leads to the conclusion that a borehole intersecting with one or both of these main fault/fissure patterns will have breakouts most likely in NE-SW and SSW-NNE directions, possible at any depth. Analysed calliper logs from well KG-25 and the first 800 m of the IDDP-1 well confirm this assumption.

Another hint that allows the detection of possible zones of wellbore failure is the distribution of fracture zones and permeable fractures, which can be inferred from lost circulation zones encountered during drilling, examination of cores and cuttings, and distribution of micro earthquakes. By processing this information possible zones of wellbore failure can be detected and the mud engineer can act accordingly to adjust the constitution of the drilling mud to prevent excessive mud weights.

For those intervals that are also spot-cored, this uncertainty can be resolved by direct observation and measurement of the fractures obtained by core analysis. The deep reservoir is probably less permeable, but the fracture density is probably not lower as in the upper reservoir. The great difference of temperature in the two reservoirs is also expected to be independent of fracture density.

The current and recent stress states in the Krafla geothermal field can be deduced from analysis of geophysical logs, micro earthquake data, ongoing seismic studies and the investigations of exposed fractures and veins. This information in turn permits an assessment of the stress field leading to the statement of most probable borehole failure conditions. But without this data only general interpretations like those stated above are possible. Based on this information, the probability of intersecting fractured zones, which favour borehole failure, is given at any depth independent of temperatures. This risk is assessed to 50%.

If the wellbore pressure is improperly adjusted at any point during the drilling and well completion process, the wellbore may experience degraded functionality or become entirely dysfunctional. All but the most minor wellbore failures have a significant impact on the completion of the well. Thus the impact factor is determined to be 3.

As stated above, a good geomechanical model based on the investigation of rock properties on the drilling site is of major importance. Pre-drill planning incorporating a geomechanical analysis of stress and wellbore failure to minimize stability problems has been demonstrated to be extremely cost-effective for wells (van Oort et al., 2001). During drilling, the geomechanical model can ensure, by giving the right mud weights, that a functional wellbore is constructed efficiently and free of formation fluid influx, drilling fluid loss, or wellbore instability. However, data uncertainties can be quite large due to a number of factors, and thus there are often large uncertainties in the predictions of the safe range of mud weights appropriate to avoid stability problems. By applying Quantitative Risk Analysis (QRA) software it is possible to quantify the mud weight uncertainties using reasonable estimates of the uncertainties in the input data, and to establish the benefits of additional measurements to reduce those uncertainties and thereby reduce the risk of later drilling problems (Moos et al., 2003).

5.6 Casing Failure

To obtain a sustained flow of steam from a reservoir, it is necessary to choose an appropriate diameter for the production well. Additionally, it is necessary to provide adequate casing at correct depths to prevent hot water from higher formations from entering into the well. For the sake of longevity, the casing must be capable of withstanding wear, corrosion, high temperatures and attrition due to friction and vibration. The temperature to be expected in the well is higher than in conventional geothermal wells and much higher than is experienced in the petroleum industry. The bottomhole temperature is assumed to be 550°C and the flowing well head temperature is estimated to be 500°C. The pressure is expected to be 25 to 27 MPa (3600 to 3900 psi). In the design of geothermal wells the guidelines of the petroleum industry have been followed but when the temperature exceeds 150°C the geothermal industry have been using ASME and ASA codes as suggested in NZS 2403:1991, the New Zealand Code of practice for deep geothermal wells.

The temperature changes cause strain (tension or compression) due to hindered thermal expansion of the casing, partially offset by a possible state of traction that may have been produced during the hardening of the cemented annulus. Thermo-mechanical modeling before and during drilling to forecast potential damage can be a solution to minimize thermal stresses.

It was decided to weld the connections of the first three casing strings, instead of welding only the connections of the first two strings, and then use BTC connections for the intermediate casing II. It was assumed that the additional welding sections will not increase the risk of structural failure of these sections, because the production zone is considered to be sufficiently distant.

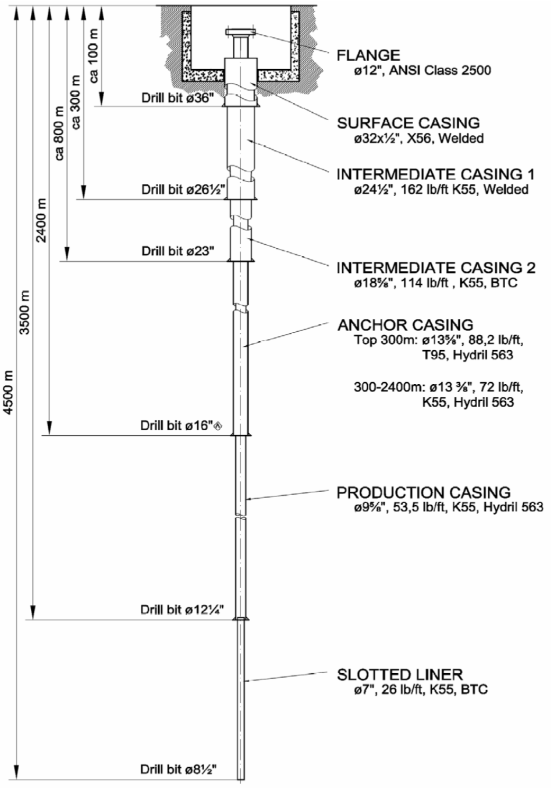

Figure 8: Casing program of the IDDP-1 well in Krafla (Palsson et al., 2008)

The combination of corrosive resistance alloys and the high-strength offered by the chosen steel types has shown good results in high temperature and high pressure wells even in a sour geochemical environment around the world for several decades now. Also, the designed casing connection types are appropriate to withstand the high temperature conditions in the IDDP-1 well, although the risk of failure is slightly increased by the decision to weld the connection of the intermediate casing II. Therefore the general failure probability for the casing program is assessed to 30%.

A failure of the casing can lead to serious delays in the drilling operation due to time consuming fish back actions of failed casing parts. In the worst case, if fishing is not possible or not successful, a cement plug has to be set and a side track has to be drilled, which will cause a serious increase in drilling costs, which is why the impact factor is assessed to be 4.

5.7 Cement Failure

Proper cementing of geothermal wells requires that the cement slurry should rise uniformly and continuously from the casing shoe to the ground level. Because it is envisaged that it will be difficult to cement the entire casing in one stage, multistage cementing will be applied. Thereby a stage tool is placed in the casing string just above the previous casing shoe. The first stage in cementing will be through cementing string through the float collar and float shoe and up to the stage tool. The second stage is present if losses are to be dealt with, between the bottom and the stage tool; a squeeze job from the stage tool can be done with the annular preventer closed. The third stage is filling up the annulus (between casings) from the stage tool. It is assumed that this more expensive and complicated multistage cementing technique will pay off in terms of securing a proper cement refill and connection of the annular space with the borehole wall or respectively with other casing strings.

Ordinary cement is adequate for temperatures up to 150°C, but to resist higher temperatures, silica is mixed with it. In geothermal wells where steam is accompanied by low-pH hot water, it is necessary to use acid-resistant cement.

Factors useful for the prediction of the risk level in cementing are bottom hole static temperature (BHST), offset experience, well deviation, water depth, temperature gradient, access to MWD temperature data, thickening time requirements and waiting-on-cement time requirements. A high risk level on one or more of these parameters may warrant the application of appropriate risk mitigation measures. The chosen cement class G will be tested by Schlumberger in Italy in terms of adding appropriate additives for the high temperature resistance capability.

One way to decrease the degree of temperature uncertainty is to collect and analyse additional temperature data while the well is being drilled. This data is most commonly obtained by MWD but could also be collected by a memory temperature sub placed in the drill string. The annular temperature data acquired from MWD can be used to calibrate a mathematical simulator, which requires the simultaneous recording of additional parameters of pump rates, circulation times, BHA depths and fluid inlet and outlet temperatures (Stiles and Trigg, 2007). A close match between the prediction from the model and the actual MWD data will increase confidence in the degree of accuracy of the simulator for cement design.

Large variations in thickening time are noted across the temperature range, which can lead to job failure and consequently redesigning the cementing procedure with different types of retarder and high temperature additives. Synthetic retarders with lower sensitivity to temperature variations may provide a good solution. Care must also be given to other slurry properties, such as fluid loss and gel strength development. If the cement system can be designed to have an adequate thickening time at the bottomhole circulation temperature (BHCT) well above what is predicted and still attain a minimum compressive strength in an acceptable time span at the BHST at the highest point of interest, then the risk of failure will be greatly reduced (Stiles & Trigg, 2007).

Refering to the given data, almost all given parameters are in the range of or even above the high risk criteria classification. By applying a multistage cementing method, the risk not to be able to cement the whole annular space up to the top is considerably reduced. On the other hand, using cement with a density of 1.9 kg/m^3 will put more strain on the pumps and casing. Therefore the overall cement failure probability is assessed to 60%.

In case of cement failure the drilling operations are delayed, which causes the common increase in drill rig costs as well as additional costs in terms of the cementing job. If the cement does not reach the surface again, even with the multistage cementing technique, cementing from the top can be a solution, although there are great uncertainties in terms of a proper refill of the annular space between borehole and casing. In the worst case the casing has to be penetrated and recemented. The impact factor in case of cement failure is assessed to 3.

6. CONCLUSIONS

The natural geological risks arising from volcanic and seismic activity are considered to be comparatively minor important factors in contrast to the well completion process due to their low probability, although their possible impact might be very serious. The risk in meeting insufficient permeable zones is assessed to be likely, but by locating and investigating upper possible feed zones it might be possible to produce superheated steam from those zones.

The main risks are assessed in the hazard of underground pressure blowouts, meeting circulation loss zones and material failures due to the high temperature environment. In addition borehole failure, formation fracturing, cement and casing failure as well as problems during coring operations are assessed to be likely, but for almost all assessed risk scenarios the failure risk can be reduced or prevented by applying appropriate techniques as well as mitigation and counteractive measures.

Due to the lack of reliable data, which also limits the risk assessment, especially for depths exceeding 2 km it makes sense to put some more effort on closing these gaps. To minimize risks and for better predictions it is recommended to investigate rock properties with the help of core samples obtained from outcrops in the drill field in advance of the drilling operation. Stress field, rock permeability, thermal conductivity, geochemical and mineralization data is of particular interest. Also, the preparation of a detailed digital reservoir model could help to understand the behavior and interactions of the different reservoirs and flow regimes. It can also help to identify the boundaries of the magma chamber in Krafla.

The entire IDDP-1 well completion is still a frontier geothermal drilling operation and therefore, in spite of all risk mitigation and prevention measures, an enterprise with great uncertainties but calculable risks. It is concluded that with a comprehensive risk management and contingency plan most of the discussed hazards can be handled.

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