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IMAGE
Integrated Methods for Advanced Geothermal Exploration

IMAGE-D5.4:
Strategy for Supercritical Well Design

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Introduction & summary

Typical high-temperature geothermal wells reach 2000-3000 m in total depth aiming for medium to high-enthalpy geothermal fluids that reach the surface as two-phase steam or in some cases single-phase saturated steam. The Iceland Deep Drilling Project (IDDP) consortium was established in 2000 (Fridleifsson, et al., 2014b) to investigate the feasibility and economics of deep, high-enthalpy geothermal resources, and supercritical hydrothermal fluids, as possible future energy sources (Fridleifsson, et al., 2014b).

IDDP-1 became the first well to be drilled in the project. Drilling came to an early end as drilling problems arose and fresh glass cuttings indicated drilling into magma. Nevertheless, the well was completed and flow tested for approximately two years with intermittent shut-in stops. The well became the hottest producing geothermal well in the world, producing superheated steam at wellhead conditions up to 450°C, pressure of 140 bar-g and enthalpy of 3150 kJ/kg (Hauksson, et al., 2014; Pálsson, et al., 2014). Although goals of producing supercritical steam, IDDP-1 was considered a success from scientific and engineering standpoint.

Drilling of the next well in the series RN-15/IDDP-2 began on 11th of August, 2016, and has now been completed. The IMAGE project has been a part of the design phase by involving scientists, engineers and other technical personnel. Strategy and design of a deep well aiming for supercritical conditions, its challenges and limitations is described in this report.

1 Background

1.1 Exploration and deep production prospects

Geophysical exploration methods, such as seismicity and resistivity, represent a key tool for investigation of the subsurface. The methods are primarily used in prospecting for natural resources and to derive information on the Earth's internal physical properties. Boreholes can then help confirm the reservoir image given by the geophysical methods.
Natural and induced seismicity occurs on reservoir fractures and faults, and the distribution over time of the earthquake hypocentres can provide an animated image of such structures. This is the base of many other reservoir characterization investigations (e.g. permeability). One example is the operation of a local seismic network at Reykjanes since 2013. It has provided data that can contribute considerably to the understanding of the nature and processes of the Reykjanes geothermal system. The depth of earthquakes from 2013 to 2016 (Guðnason, et.al, 2015) confirmed earlier observations that the brittle-ductile boundary below Reykjanes is generally at 5.5 – 6 km depth. However, based on earthquake locations including those from the data recorded by the seismic network of the Image project, an aseismic body appeared between 3 and 6 km depth, beneath the central core of the production field. The nature of this aseismic body was not known, and there was no evidence for seismic activity within this aseismic body in the past. Therefore, the proposed IDDP-2 borehole was ideal, as it was intended to enter deep into this area and could help explain the nature of the aseismic body.
The industrial aim of the Iceland Deep Drilling Project (IDDP) consortium is to improve the economics and availability of geothermal resources by aiming for supercritical fluid that transitions to superheated steam at subcritical pressures at the surface (Fridleifsson, et.al, 2014a). Potential power output per well might be increased by an order of magnitude by producing high-pressure, high-temperature steam compared to conventional wells (Fridleifsson, G.Ó. (editor); Ármannsson, H.; Árnason, K.; Bjarnason, I.Th.; Gíslason, G.; Thórhallsson, S.; Matthíasson, M.; Gíslason, Th.; Ingason, K.; Pálsson, B.M; Albertsson, A.; Bjarnason, J.Ö.; Gunnarsson, T.; Ballzus, C., 2003).

1.2 The IDDP-1 well

Drilling of the first IDDP well in Krafla, IDDP-1, began in June 2008 and was finished in July 2009. Aiming for 4000-5000 m depth, the drilling became quite challenging, including becoming stuck at 2094 and 2095 m depth. Finally, after twist-offs and two sidetracking attempts, drilling came to an end at 2096 m depth in the third leg when cuttings of fresh glass indicated the presence of a magma body at the bottom (Pálsson, et al., 2014). The well was flow tested with several different wellhead designs and was terminated on 25th July 2012 when leak was discovered form a nozzle in the wellhead. By attempting to close the well, neither of the master valves could be operated and were stuck in open positions. The situation was critical leaving no other option than to kill the well by pumping water into it (Ingason, et.al, 2014). Severe casing failures were later found in the well leading to the decision to abandon it and plug it with gravel and cement. Despite these problems, the operation was considered a success as the well became the hottest geothermal well in the world with operating temperature of 450°C and pressure of 140 bar-g (Pálsson, et al., 2014). A Special Issue of the journal Geothermics, Volume 49, pages 1-128 (January 2014), was devoted to engineering and scientific results of IDDP-1.

1.3 The IDDP-2 well (RN-15/IDDP-2)

It was decided to drill the second well in the series, IDDP-2, within the Reykjanes geothermal field, which is utilized by HS Orka. The chief motivation for HS Orka to undertake such a challenging drilling operation is to address several basic questions for commercially viable reasons (Fridleifsson, et al., 2014b):

i. Where is, and what is the nature of the base of the Reykjanes hydrothermal reservoir? Is it possibly heated by superheated steam from below?

ii. Can the deep heat sources be exploited by injecting fluid into the hot rocks beneath the most productive part of the well field?

iii. Will productive permeability be found at these great depths within the approximate centre of the fault-related up-flow zone?

iv. Does a supercritical reservoir exist at 4–5 km depth under Reykjanes or does it lie deeper still?

v. What is the nature of the ultimate heat source of this saline ocean floor related hydrothermal system; is it a sheeted dyke complex or a major gabbroic intrusion? Individual dykes may cool to ambient temperatures in a few years, depending on thickness, while large gabbro intrusions may act as a heat source for thousands of years.

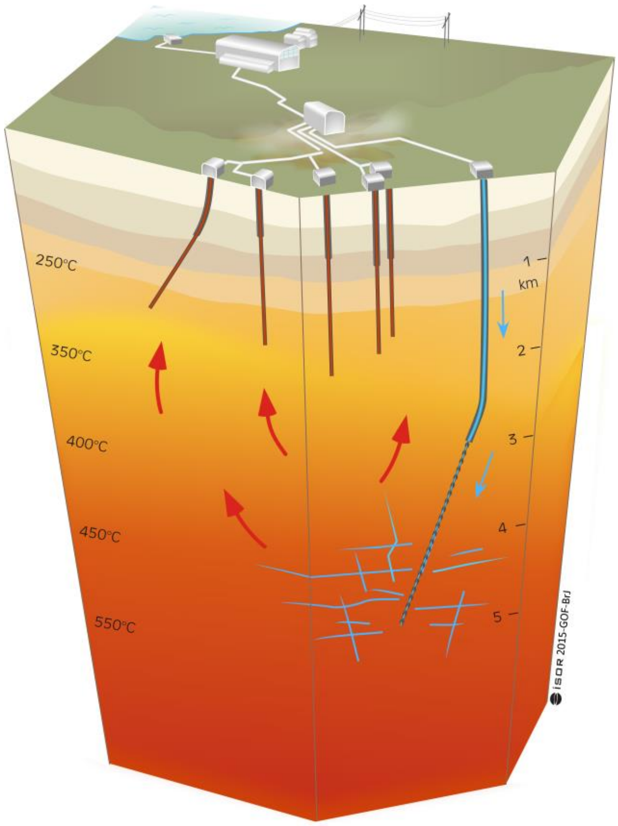

Figure 1. *Concept diagram of the roots of the Reykjanes geothermal field indicating existing wells (brown) and deep well within the system (blue) intersecting supercritical zone beneath the producing reservoir* (Fridleifsson & Elders, 2017).

A start-up meeting for the design phase of IDDP-2 was held in September 2013. The meeting included experts from the geothermal industry, including IMAGE members. After the meeting, HS Orka divided the design of the well up into three technical groups: i) well design, ii) flow testing equipment and iii) chemistry. The well design group consisted of participants from HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, ÍSOR, University of Iceland and the principal designer of the well Mannvit who were responsible for the final design. The objective – to design a well for supercritical conditions down to 5000 m depth (Figure 1). In the initial plans, the well was designed as a new well, before a “well of opportunity”, located in the Reykjanes geothermal area, was selected. At later stages, it was decided to use and deepen existing well RN-15, which became the “well of opportunity”. The well was already 2507 m deep and included three casings, the narrowest 13 3/8” production casing. For reference to RN-15, the IDDP-2 well became RN-15/IDDP-2.

In December 2015, RN-15/IDDP-2 became a part of European Union project DEEPEGS funded under Horizon 2020. A joint effort of the IDDP-Consortium and DEEPEGS, kick-off meeting for the RN-15/IDDP-2 well, was held on the 23rd of June, 2016 (www.iddp.is) where the drilling plan and timeline for RN-15/IDDP-2 was presented. Funding for IDDP spot coring has been provided by the International Continental Scientific Drilling Program (ICDP) and the US National Science Foundation. The drilling of the well began on 11th August, 2016 and was completed to 4659 m depth on the 25th of January, 2017 (www.iddp.is).

2 Well design

2.1 Design considerations

Design phase of a typical geothermal well includes several tasks, including: determining design temperatures and pressures at static and dynamic flowing conditions, casing depth selections, casing selection and structural design, drilling program and well completion, and after completion, plan for warm-up and flow-testing.
For design purposes the formation lithology and its conditions provide vital information on targeting, drilling procedure and wellbore integrity. Temperature and pressure (TP) profiles in nearby wells are used to estimate likely TP conditions. In such a deep well, the critical point of water will be encountered at ~3500 m depth assuming hydrostatic column of pure water at boiling conditions (boiling point curve). The depth is however dependant on where the pivoting point of pressure (or the water table) is located in the well as well as salinity of the fluid. Salinity effects on the boiling-point depth curve (BPD) is that pressure and temperature are slightly increased downhole and the critical point is reached at a greater depth (Ingason, et al., 2015). Below the critical point the density of the fluid is assumed to be either with a fixed gradient or isochor representing pressure corresponding to changes of temperature of fixed volume of steam (Thorhallsson, et al., 2010).
Maximum working pressure and temperature estimated during drilling and production is estimated from the assumed downhole subsurface conditions, i.e. maximum design pressure for depth, assuming that the well is filled with saturated steam from the well bottom. Or for such deep well, the assumption is that the well will be filled with superheated steam rather than saturated. The general design condition for minimum casing depth selection is that a column of heavy mud (SG 1.4) inside the longest casing at any time during the well construction is able to balance the pressure from a blowout in the next open hole section (Ingason, et al., 2015). Furthermore, in a new edition of the New Zealand standard, NZS2403:2015 *Code for practice for deep geothermal wells*, to ensure well control the formation fracture pressure is used and the minimum casing depth selected where the formation has sufficient effective containment pressure to equal the maximum design pressure expected in the next open hole section.
Material selection for geothermal wells has conventionally been standard low grade API casings. Recommended geothermal steel grades to avoid corrosion effects in H_2S environment are defined in standard NACE MR0175 (ISO 15156-1). In Reykjanes the geothermal fluid is thermally modified seawater and the chlorine (Cl) concentration in the reservoir fluids is similar to that of seawater (Fridriksson, et.al, 2015). However, deep in the system at 5 km depth the chemistry and state of the fluid is not known and scenarios regarding the anticipated fluid chemistry in a deep well in Reykjanes is thoroughly described by Fridriksson et.al 2015. From chemical standpoint, three scenarios are described; (i) most favourable and manageable low temperature scenario where similar fluids will be produced as currently are produced from the Reykjanes field with additional silica concentration and potential for metal sulphide scaling, (ii) second most favourable conditions where superheated steam at 550°C with complicated fluid of high concentration of silica in the steam and presumable high HCl content is expected to be produced from the well and (iii) the least favourable condition of intermediate temperature where either two fluids, high salinity – high density brine and low salinity – low density fluid, may coexist or only superheated steam at about 440°C where the condensate which forms during decompression will be extremely acidic as HCl in the steam will preferentially partition into the condensate, resulting in acute corrosion problem in the well. In all cases careful material selection is essential.

Structural design of casings and wellhead need careful considerations as thermal stresses/strains and pressure will be higher than in conventional wells. Structural strength of steel lowers at elevated temperatures. Increased temperature of deep wells therefore provides difficult structural challenges that may limit current drilling and well completion technology.

2.2 Well of opportunity

In 2005 the IDDP plan was to deepen existing well RN-17 in Reykjanes to 5 km depth, however, prior to deepening the well it collapsed during a flow test and could not be used as a “well of opertunity” (Fridleifsson, et.al, 2014a). The operation was therefore moved to Krafla operated by Landsvirkjun where the IDDP-1 well was drilled. Initial plans for drilling IDDP-2 in Reykjanes were to drill a new well aimed for 5 km depth. This well had already been designed when it was decided to use and deepen to 5 km depth an existing well, RN-15, already 2507 m deep, located within the geothermal field (Figure 2).

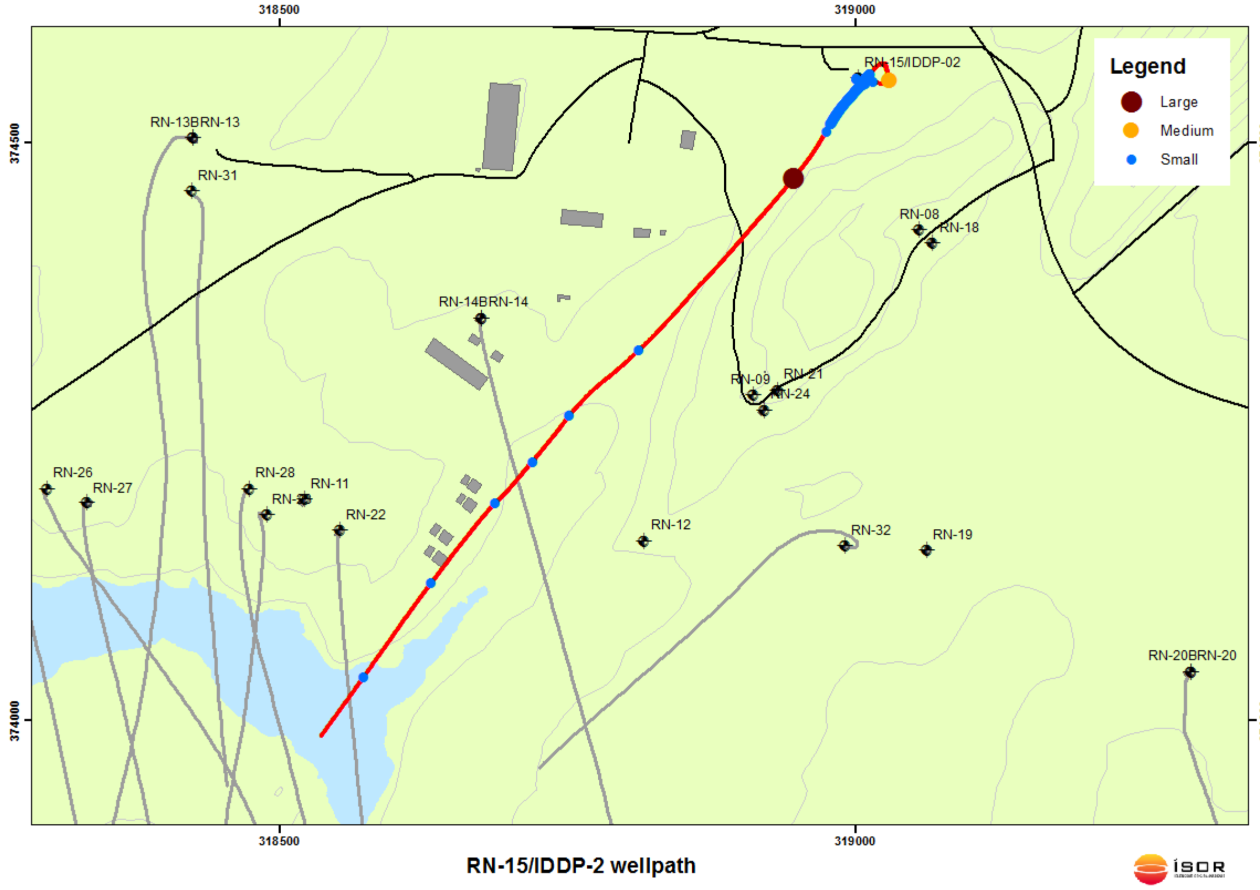

Figure 2. *Areal photograph showing the location, wellpath and feed-zones of RN-15/IDDP-1 at Reykjanes* (Fridleifsson G. , et al., 2017).

Using a “well of opportunity”, put constraints on the design that was already constrained by high temperature and pressure conditions. The RN-15 well (Figure 3) already had three existing casings, 22½” surface casing down to 87 m, 18⅝” anchor casing to 293 m and 13⅜” production casing to 794 m. These became the surface casing and intermediate casing 1 and 2 of the RN-15/IDDP-2 well.
In depth selection for the production casing there was an emphasis on sealing off the upper production reservoir by installing and cementing 3000 m casing, the longest casing to be installed in a well in Iceland. In casing design, the casing needs to withstand pressures and temperatures for all drilling phases as well as the production phase. The well was designed according to New Zealand standard NZS2403:1991 “*Code of practice for deep geothermal wells*”. Note that the well had been

designed and preparations for drilling were underway, when a new revision of the standard was released in 2015, the well was therefore designed by using the older version.
Despite constraints in design, conventional design methods were used with the exception of more careful material selection, using a method of reverse cementing instead of the conventional inner string method, and adding a sacrificial casing to meet design criteria.

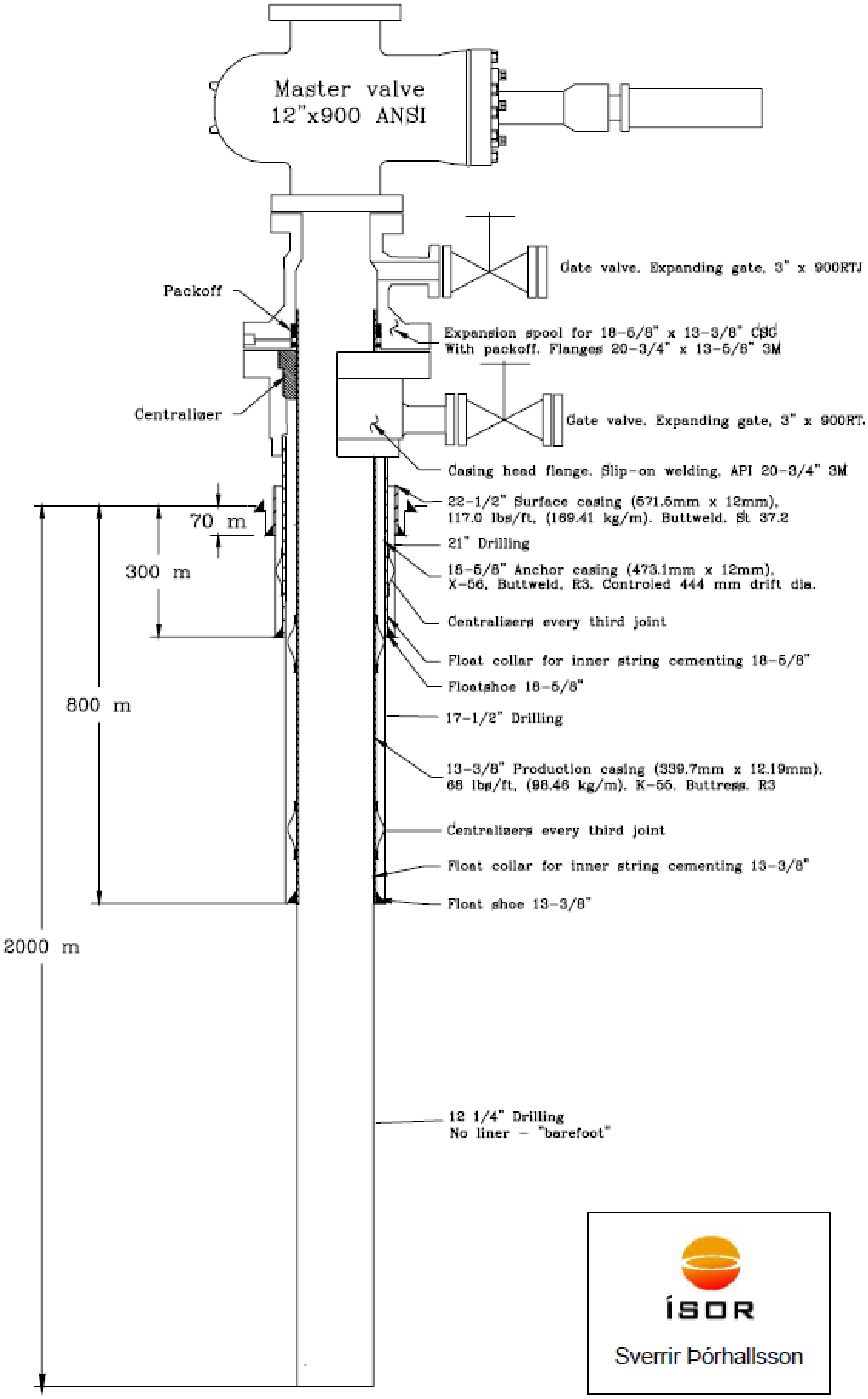

Figure 3. *Casing program of well RN-15* (Gautason, et al., 2004).

2.3 Casing design

Casing materials and casing design have in past decades been designed with available API standard materials. The New Zealand standard NZS 2403:1991 "*Code of practice for deep geothermal wells*" has been the backbone in casing and wellhead design and in the year 2015 it was updated to NZS 2403:2015, with modified recommendations for casing depth selection, design factors, design curves and more.
Conventional casing specification and design is based on axial compressive and tensile loads, and differential pressure between the inner and outer casing wall. Anticipated load cases during drilling and after well completion, and design steps to avoid common failure modes are included in the New Zealand standard.
Generalized casing design steps are as follows (further described in the New Zealand standard);

1. Gather all data on the site and formation conditions including:
    a. Geological lithology of the formation
    b. Temperature and pressure conditions with depth
    c. Conditions of the formation and anticipated problem zones, such as lost circulation depths and information on loose formations
2. Define the maximum pressure and temperature profiles with depth
3. Calculate overburden and fracture pressure of the formation with depth
4. Calculate the minimum casing shoe depths with the criteria of well control for each drilling phase
5. Decide the desired open-hole diameter of the well
6. Calculate for all casings, strength against loads during casing installation, cementing and production
7. Design iteratively by revising the design if any changes are made

For deep wells, where the design pressure at depth at around 3500-4000 m will be higher than the critical point, assumptions on the pressure changes with increased depth of the fluid need to be taken. Once maximum pressure and temperature profiles have been defined and containment pressure for depth calculated, minimum casing shoe depths can be determined. The minimum casing shoe depth varies depending on selected criteria, which needs to be evaluated for each case. Once casing shoe depths have been selected, structural calculations for each casing string is calculated, these include (further described in the New Zealand standard):

1. Axial tensile stress during running and cementing casing
2. Burst and collapse calculations during cementing
3. Burst and collapse during production of steam
4. Compressive thermal loading (strain)
5. Bi-axial tensile stress due to wellhead pressure
6. Helical buckling of liner

These calculations determine which casing sizes, connections and materials can be selected for the well. Once these design steps are complete, a casing program is proposed for the drilling program. A casing program of the RN-15/IDDP-2 well, designed by Mannvit, can be seen in Figure 4. Setting depth of the production casing was selected as 3000 m to isolate current production zones of nearby wells (Ingason, et al., 2015). The casing program is unconventional, as it is a continuation of a previously drilled well. The master valve is installed on the 3000 m long production casing which by definition becomes the anchor casing. A sacrificial casing is installed and cemented within the production casing (anchor casing) from top to 1300 m depth. The material selected for the sacrificial casing is Tenaris high collapse sour service grade TN 80HS which manufacturing process is strictly controlled, lowering the probability of corrosion cracking due to presence of H_2S and lowering possibility of collapse failure due to increased roundness of the pipe. Other modification from standard well design is that a higher grade material, L80 instead of conventionally selected K55, was selected for the production casing (anchor casing).

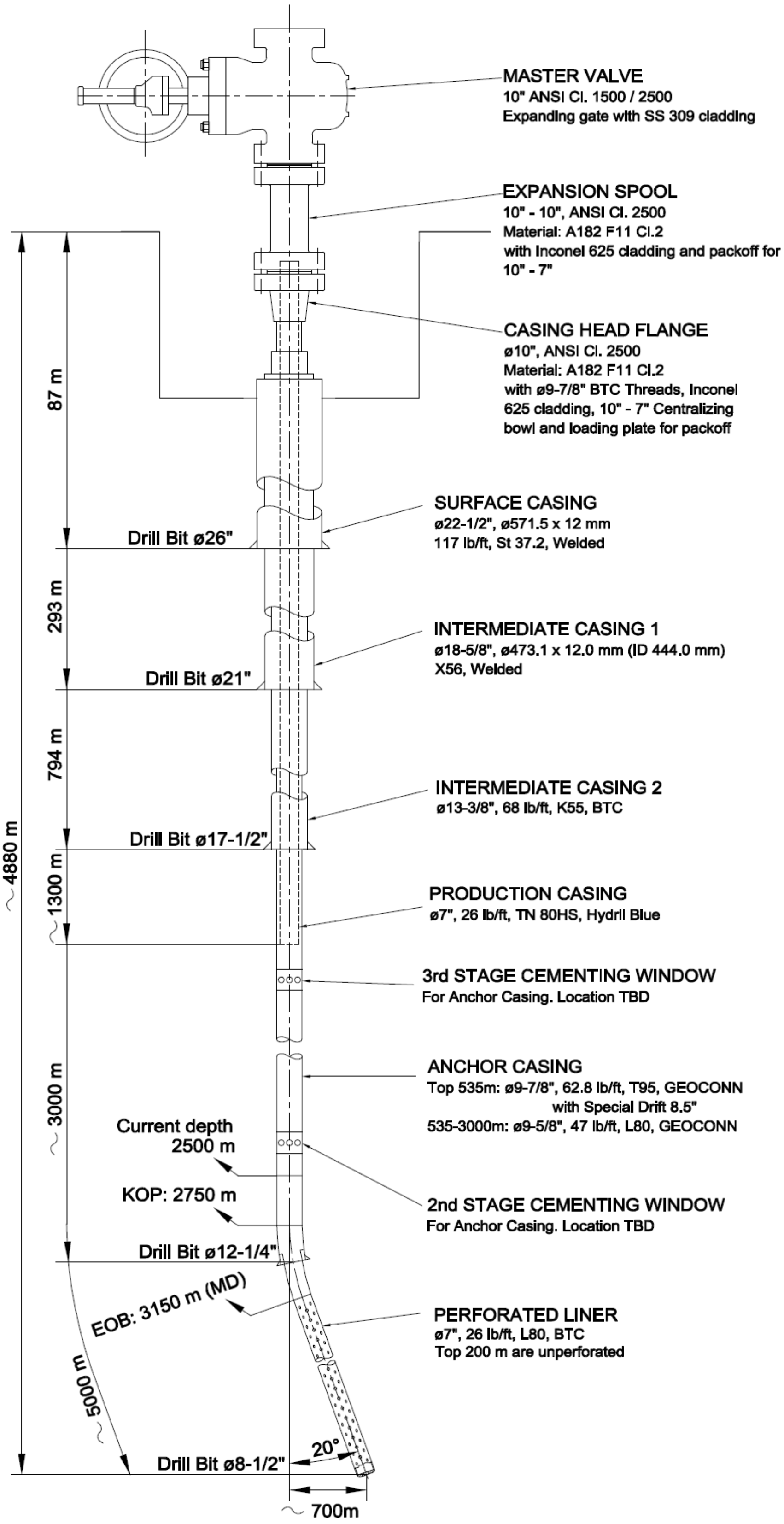

Figure 4. *Schematic drawing of well RN-15/IDDP-2, casing and well-head design (published with permission from Mannvit, 4-LBA-3002)* (Weisenberger, et al., 2016).

Casing connections buttress threaded connections (BTC) have shown good results for conventional geothermal wells. In wells that have high wellbore temperatures (>200°C), thermal expansion generates stresses that surpass the strength of the steel, leading to permanently straining the material due to high compressive force in the material. The axial compressive force can also induce collapse-bulge of the casing. In cases where the wellbore temperature decreases again from hot conditions, tensile forces can rupture the casing. Several examples of casing failure of tensile rupture at the couplings have been seen in hot wells in Iceland. For increased structural integrity in compression, connections that allow the compressive force to flow through the coupling instead of through the threads have been selected. These connections however do not improve the structural integrity of the casing in compression or in tension as thermal strains are still formed due to axially constrained casing. A design factor for axial compression due to thermal expansion has been dropped out of revision of the New Zealand standard as the requirement is impossible to be met for most high-temperature geothermal wells, instead, acknowledging that permanent plastic strains are produced, in the new revision plastic/strain-based design is required.
Connection solution, flexible couplings (patent pending), that allows axial expansion which relieves thermal stresses in the casing, have been in development in the H2020 project GeoWell (geowell-h2020.eu) since late 2015 and are also a part of H2020 project DEEPEGS (deepegs.eu) (Kaldal & Thorbjornsson, 2016) (Thorbjornsson, et.al, 2017). Flexible couplings were considered for RN-15/IDDP-2 but as the couplings were not ready for manufacturing in time for drilling, it was decided not to use them in the well.
When the production section of wells has been drilled, in most cases, in order to avoid collapse of the well a perforated liner is hanged from the production casing shoe down to the total depth of the well.

2.4 Cementing of casings

Initial plans for cementing IDDP-2 included stage cementing tools (Ingason, et al., 2015), where cementing windows on the casing are opened and closed during the cementing procedure. At later stages it was however decided to simplify the operation by excluding all complications. Instead of using the conventional cementing method of the inner string method, where cement is pumped though the drill-string though stab-in and float collars and up the annulus, a reverse-circulation cementing (RCC) method was used (www.iddp.is). Using the RCC method the cement is pumped directly into the annulus. The benefit of using reverse cementing is that less cement is lost to the formation and lower load is subjected on the casing allowing for cementing deeper casings. Conventional cementing methods can cause excessive cement waste and associated costs, and expensive retarders can increase the cost further (Hernandez & Bour, 2010). Advantages of reverse-circulation cementing include (Hernandez & Bour, 2010):

1. Reduced hydraulic horsepower as the gravitational force is working in favor of the slurry flow.
2. Reduced downhole pressures which works in advantage for not fracturing the formation and puts less load on the casing.
3. Shorter transit and thickening times of the slurry.
4. Improved compressive strength development of the cement as most of the cement will not see the shoe bottomhole temperatures.
5. Less cement waste primarily because no excess cement is pumped back to the surface.

Cement blends that are used for high-temperature geothermal wells require blending of additives to ensure longevity and API specification recommend Portland API Class G cement blending up to 40% by weight of cement (BWOC) of silica flour to prevent strength retrogression and increased porosity when exposed to elevated temperatures (Hole, 2008). Special proprietary blends, e.g. Dyckerhoff cement, have also been used in geothermal operations and was used in IDDP-1 with good results although multiple problems, not connected to the cement blend used, arose during cementing operations. Innovation in cement design for high-temperature applications are currently ongoing in several projects, with aim of lowering frictional pressure losses, lowering water content and improving strength characteristics.

2.5 Wellhead

Wellhead with sufficient pressure rating is selected from the maximum design pressure and temperature. In conventional wells, the maximum design pressure is assumed to be from a well filled with saturated steam from the bottom of the well to the top, where the bottom hole pressure and temperature conditions is assumed to follow the boiling point depth curve (BPD). For a superheated well, it can be assumed that the well is filled with isenthalpic superheated steam from the bottom, with assumption that from the critical point, the bottom hole pressure increases with depth according to a fixed gradient or other assumption mentioned before. From the IDDP-1 experience, it is clear that the pressure difference between bottom hole and the wellhead is governed by the weight of the steam column in the well and frictional pressure drop is negligible (Ingason, et al., 2015). The wellhead conditions of RN-15/IDDP-2 of temperatures >345°C to <500°C and pressures of 155 to 250 bar are likely, judging from several thermal gradient estimates (www.iddp.is).
The wellhead master valves from IDDP-1, pressure rating of ASME Class 1500 valve with Class 2500 flanges and material type 1.9 (Ingason, et al., 2010), were improved and refabricated and used for RN-15/IDDP-2 (Fridleifsson & Elders, 2017).

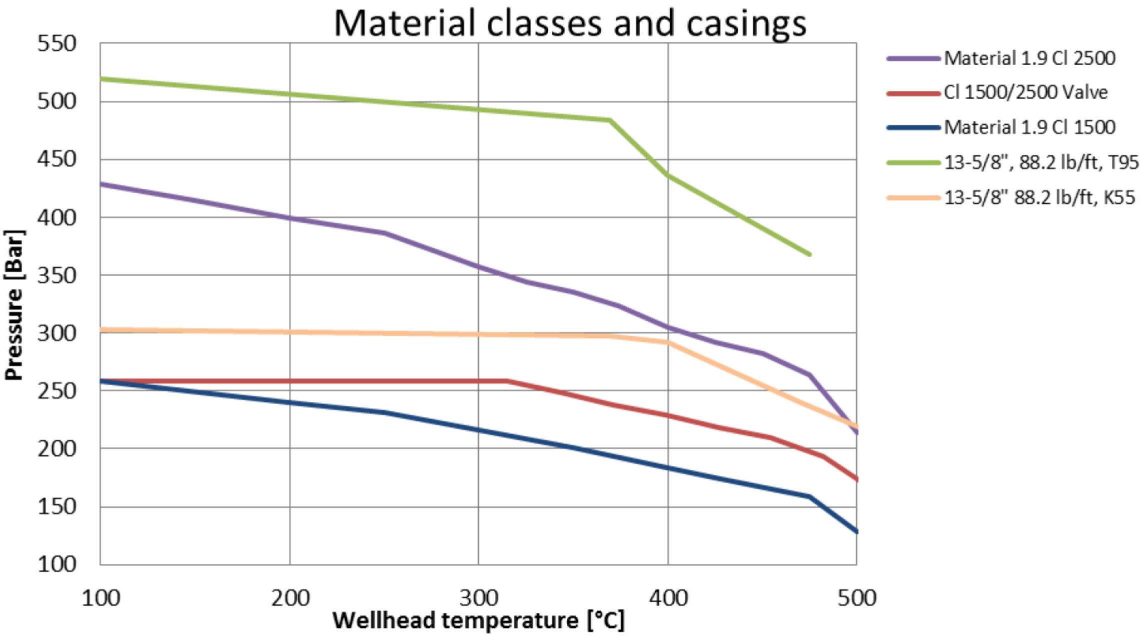

Figure 5. *Pressure rating as a function of temperature for a wellhead with ASME Class 1500 wellhead valve combined with ASME Class 2500 flanges and for conventional ASME Class 1500 wellhead* (Ingason, et al., 2015).

2.6 RN-15/IDDP-2 as built

The as-built casing program of the well is shown in Figure 6 and Table 1 shows depth information referenced to the ground level. The casings already installed in *the well of opportunity* RN-15 were a 22½" surface casing, an 18⅝" anchor casing and a 13⅜ production casing (Figure 3). These casings now serve as surface casing and intermediate casings 1 and 2. A new production casing was installed in the well. It also acts as an anchor casing by definition as the wellhead is attached to it. Its top 445 m are made of 9⅞", 62.8 lb/ft, T95 grade casing with GEOCONN connections and the lower section is made of 9⅝", 47 lb/ft, L80 grade casing with GEOCONN connections. A 7", 26 lb/ft, L80 grade perforated liner with buttress threaded connections (BTC) hangs inside the production casing (anchor casing) at about 2871.2 m measured depth and reaches down to 4591.2 m measured depth. Lastly a 7", 26 lb/ft, specially selected grade Tenaris High Collapse and Sour Service TN 80HS liner with Tenaris Hydril Blue® connections was installed from ground level to measured depth of 1303.7 m (Weisenberger, et al., 2017). The 10” expanding gate master valves from IDDP-1, pressure rating of ASME Class 1500 valve with Class 2500 flanges and material type 1.9 (Ingason, et al., 2010), were improved and refabricated and used for RN-15/IDDP-2 (Fridleifsson & Elders, 2017).

Table 1. *Casing program as built of RN-15/IDDP-2* (Weisenberger, et al., 2017).

Casing	Note	Nominal size (OD)	Measured depth (ground level) (m)	Nominal weight (lb/ft)	Steel grade	Connections
Surface casing	Installed in RN-15	22½"	84.4	117	St 37.2 (S235JR)	Welded
Intermediate casing 1	Installed in RN-15	18⅝"	292.8	N/A (12 mm)	X56	Welded
Intermediate casing 2	Installed in RN-15	13⅜"	793.8	68	K55	BTC
Production casing (anchor casing)	RN-15/IDDP-2	9⅞"	Top 445	62.8	T95	GEOCONN w. special drift 8.5"
Production casing (anchor casing)	RN-15/IDDP-2	9⅝"	445 – 2932.4	47	L80	GEOCONN
Sacrificial casing	RN-15/IDDP-2	7"	0 – 1303.7	26	TN 80HS	Hydril Blue
Perforated liner (top 189.7 m are not perforated)	RN-15/IDDP-2	7"	2871.2 – 4591.2	26	L80	BTC

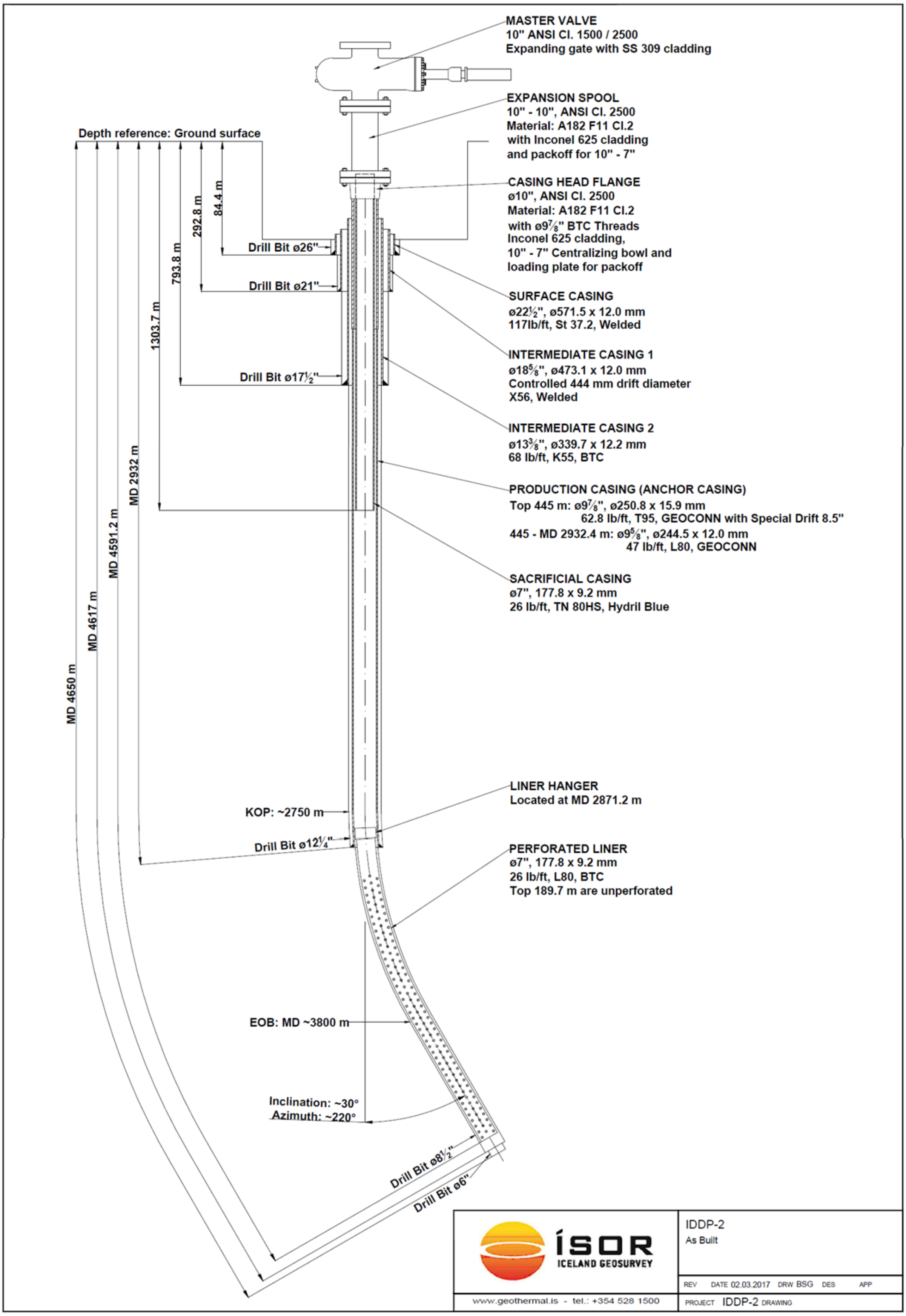

Figure 6. *Schematic drawing of well RN-15/IDDP-2 as it was built. The well was designed by Mannvit* (Weisenberger, et al., 2017).

3 Conclusions

In this report, strategy for supercritical well design, possible scenarios and design considerations have been described. When this report is written, drilling of a deep well in Reykjanes aiming for superheated/supercritical fluid conditions has already been performed and the well is being stimulated. In the IMAGE project, the drilling of the deep well in Reykjanes was anticipated to take place at later stages. Therefore, the reporting here is partly a summary for well RN-15/IDDP-2 as well as a general strategy for deep well design. The learning curve of design and drilling deep geothermal wells aiming for superheated/supercritical conditions has been steep and many challenges have been solved along the way over the past decade (and decades). However, some challenges remain unsolved still and undoubtedly more will emerge in future deep drilling projects. Proper material selection for such harsh environment, fluid handling, well control, casing and wellhead design for stable structural integrity are key for utilizing future deep geothermal resources.

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