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Design of Superhot Wells

Kristinn Ingason, Þóroddur Sigurðsson

Mannvit, Urðarhvarf 6, 203 Kópavogur, Iceland

kristinn@mannvit.is

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ABSTRACT

The interest for researching and utilizing superhot geothermal resources has been increasing. The Iceland Deep Drilling Project has led the way, but other projects have followed such as in Japan, New Zealand, Mexico and Italy. Drilling a well into the superhot reservoir and which is suitable for the geothermal fluid expected, is obviously most important for developing this concept. The casings need to be deeper compared to conventional geothermal wells, challenges related to thermal expansion are greater and the fluid chemistry is likely to be more difficult to deal with. An overview is presented of well design in projects where drilling into superhot geothermal resources is planned. The extreme design conditions are discussed along with the associated challenges which need to be solved. The discussion will include some of the lessons learned when drilling and operating wells IDDP-1 and IDDP-2.

1. INTRODUCTION

Drilling for and utilizing fluid from superhot geothermal resources may be a feasible way of utilizing geothermal energy. The main opportunities are related to higher output of energy rich fluid from production wells. Therefore, fewer wells need to be drilled, footprint of the power plant will be smaller, electrical generation more effective and opportunities may be to expand existing power plant by drilling below existing wells and increase the size of the reservoir by deepening it. The most critical component in this kind of utilization will be the wells. They must be designed to withstand the high temperature and aggressive chemistry of the fluid and challenges during drilling must be solved. This is being discussed in the following.

2. OVERVIEW OF DRILLING INTO SUPERHOT GEOTHERMAL RESOURCES

Three projects have completed wells that have been specifically aimed at superhot/supercritical geothermal systems. These are the IDDP-1 and IDDP-2 in Iceland and the DESCRAMBLE project in Larderello, Italy.

Numerous other exploration and production wells around the world have unexpectedly encountered superhot/supercritical conditions. In those cases, most of the wells had to be plugged and abandoned as the well design was not suitable for these conditions. There have been documented wells that have reached superheated/supercritical conditions in Italy, Iceland, Japan, US, Mexico and Kenya.

The highest temperatures encountered have been in Japan in Kakkonda, well WD-1a where 500°C was encountered at 3729 m depth, IDDP-1 where up to 450°C was measured at the wellhead and estimation of 900°C magma being penetrated, and in KS-13 in the Puna Geothermal Field in Hawaii, where the temperature downhole was not measured but petrological study of dacitic glass that was recovered suggests that it had a temperature of ≈1050 °C (Reinsch, T. et al., 2017).

2.1 Completed Projects

IDDP -Iceland Deep Drilling Project (www.iddp.is)

The main purpose of the IDDP project is to explore if it is economically feasible to extract energy and chemicals out of hydrothermal systems at supercritical conditions. The idea of the IDDP is to drill deep enough into the roots of a conventional high temperature hydrothermal system to produce water at supercritical conditions and bring it to the surface as 400-600°C superheated steam, at subcritical pressures (<220 bar).

IDDP-1 in Krafla field, Iceland.

The first IDDP-1 well was meant to be completed to 4.5 km depth late summer 2009, followed by flow testing. However, that drilling operation was abruptly terminated by late June at 2.1 km depth when drilling penetrated molten rock. Rapidly quenched magma of rhyolitic composition was returned to the surface in the form of quenched obsidian glass that plugged the lowest 20 m of the hole. Fortunately, due to earlier drilling problems, the well had been cased down to 1958 m depth and was completed with a slotted liner down to 2080 m depth.

The IDDP-1 well was extensively tested and became the world's hottest production well for a while, yielding 452°C hot superheated steam at 140 bar pressure with production potential of up to 36 MW_e (SAGA REPORT No. 10, 2016)

The well discharged at intervals for almost two years, in July 2012 the well had to be quenched when the master valves failed. The well was inspected with downhole camera after the quenching and serios damages of the casings were found. The well was plugged and abandoned in October 2015 after various samples had been collected and inspected.

IDDP-2 in Reykjanes, Iceland (SAGA REPORT No. 11, 2018)

The IDDP-2 well used the previously drilled HS Orka´s well RN-15 which was 2,500 meter deep production well. Initially the RN-15 well was deepened to 3,000 meters and the new production casing was cemented to the surface. The deepest existing geothermal wells at Reykjanes at that time were approximately 3,000 meters deep but know the IDDP-2 has the deepest casing in any well in Iceland. The 8-1/2" production section was then drilled down to 4,650 m MD. The drilling of the IDDP-2 well at Reykjanes began 11th August 2016 and ended 25th of January 2017 after 168 days of drilling operation. Temperature at the bottom of the well was measured at 426°C, during drilling, at fluid pressure of 340 bars. It immediately became clear that the bottom of the well had reached fluids at supercritical conditions, so the main drilling phase objective of the IDDP project had been achieved. Over 20 m of coring were successfully retrieved from the well bottom. In May 2017 temperature logs during and after a warm period of only a few days suggested a stable bottom hole temperature at least 535°C.

The production casing is damaged at roughly 2300 m, probably due to a long uncemented section. The well has been heating up for several months and discharging of the well is planned later this year.

DESCRAMBLE: Drilling in dEep, Super-Critical AMBient of continentaL Europe (http://www.descramble-h2020.eu)

DESCRAMBLE's scope was the development of new drilling technologies and concepts for geothermal energy exploitation from deep and super-critical geothermal resources in continental geological condition in Europe. DESCRAMBLE's specific objectives were:

- Demonstrate safe drilling of a deep super-critical geothermal well.
- Reduce the technical and financial risks of drilling and exploiting deep geothermal wells by improving knowledge of the physical and chemical conditions in deep geothermal formations.
- Reduce pre-drill uncertainty in the exploration of deep geothermal wells by applying the latest seismic processing, imaging and interpretation technology for exploring the supercritical reservoir prior to drilling.
- Investigate the economic potential of exploiting chemicals and minerals by analyzing fluid samples for valuable material.

The descramble project succeeded in deepening of an existing well Venelle-2 from 2.2 km down to 2.9 km depth, reaching temperature of 507-517 °C, pressure of about 300 bar but no sign of fluids (Manzella, A. and Bertani, R., 2018)

2.2 Ongoing and Future Projects

Krafla Magma Testbed (www.kmt.is)

The Krafla Magma Testbed (KMT), Krafla Caldera, Iceland, is proposed to be the first magma observatory, an international multi-borehole facility where teams will conduct scientific experiments and engineering tests focused on the magma-hydrothermal interface in superhot geothermal systems (Eichelberger, J. et al., 2018).

Preparations are underway for drilling well KMT-1 of the Krafla Magma Testbed at Krafla, Iceland to sample and instrument the margin of a rhyolite magma body. The total depth of the well is planned to be 2100 m with cemented casings down to 2040 m and an 8 ½" open hole section for coring to 2100 m. The geology for KMT-1 is well known and the well will be located close to the IDDP-1 well where magma was unexpectedly intersected at 2.1 km depth in 2009 (Holmgeirsson, S. et al., 2018).

GEMex Geothermal Cooperation Europe Mexico for EGS and super-hot geothermal systems (www.gemex-h2020.eu)

The project is a complementary effort of European and Mexican consortiumS. The joint effort is based on three pillars: 1. Resource assessment 2. Reservoir characterization 3. Concepts for site development. (http://www.gemex-h2020.eu)

This project is currently still ongoing. The third part of project (Concepts for site developments) aims to develop and verify concepts and technologies to access and exploit super-hot reservoirs (>300°C, including conditions above the critical point of water in the reservoir). The concept for the development will also include material issues related to thermal stresses, corrosion and scaling all of which are critical for successfully producing in superheated/supercritical environments (http://www.gemex-h2020.eu).

GeoWell (http://geowell-h2020.eu/)

GeoWell is another Horizon 2020 collaborative research project which aims at developing reliable, cost effective and environmentally safe technologies for design, completion and monitoring of high-temperature geothermal wells. Topics for research include cement and sealing technologies, materials and coupling of casings along with temperature and strain measurements in wells using fibre optic technologies to monitor well integrity.

One of the outputs from GeoWell has been the design and development of the Flexible Coupling, which is aimed at reducing the risk of plastic deformation and collapse of casings. The Flexible Coupling allows for thermal expansion of casing segments, which is one of the major concerns in the operation of high-temperature geothermal wells and relates to structural damages during warm up and discharge after drilling (Thorbjornsson, I. et al., 2017).

Japan Beyond Brittle project (JBBP)

The JBBP was started to investigate the feasibility of developing an EGS in brittle–ductile transition (BDT) zone. This project started as a result of encountering high temperatures (500°C) in Kakkonda, Japan. Currently there are research projects ongoing and the aim is to locate a suitable site and drill into a supercritical system.

3. DESIGN CONDITIONS

The depth of wells to be drilled into superhot reservoirs have been planned to be up to 4500 - 5000 m deep. This was the plan for IDDP 1 although its final depth was less than half of the planned one, after drilling into magma at 2100 m. The depth of IDDP 2 is about 4500 m as was planned.

The conditions downhole are estimated by assuming a temperature profile and calculate the pressure assuming hydrostatic conditions. Logging data from the wells are used if available but when not available the fluid is assumed to be boiling and temperature follows the boiling point with depth curve. The curve may have to be adjusted to chemical properties of the fluid such as salinity as was the case for IDDP 2. Once past the critical point of the fluid, the temperature gradient assumption becomes more uncertain. One scenario has been to assume a linear gradient of 0.1 °C/m.

In Figure 1, two scenarios for temperature are presented. The fluid is assumed to be dilute with the same properties as pure water and the water level in the well is assumed 200 m.

Scenario 1: Boiling point with depth down to the critical point and thereafter temperature gradient of 0.1 °C/m

Scenario 2: Linear temperature increase from water level down to 700 m, boiling 700 – 1100 m, constant temperature of 290 °C down to 3000 m and thereafter linear gradient of 0.12 °C to well bottom.

The general form of the temperature profile presented in scenario 2 is more in line with observations in high enthalpy geothermal fields, although the gradient at the bottom is uncertain.

The temperature according to these two scenarios result in the pressure profiles shown to the left in Figure 1. Scenario 2 results in higher pressure in the well, which is in accordance with logging of IDDP wells, and the temperature could also be higher at the well bottom although that is not assumed in the scenarios presented here.

The pressure profiles in the well for the two scenarios is presented in Figure 2. The maximum pressure at wellhead is about 30 bars higher in scenario 2 compared to scenario 1, i.e. 232 bar vs. 202 bar. The wellhead temperature is roughly the same in both cases, 440 °C.

The fracture pressure is evaluated according to Eaton's formula and assuming a Poisson's ratio of 0.35. The production casing must be deep enough to prevent fluid from the upper part of the reservoir to flow into the well. Assuming it will be 3000 m deep and to ensure the integrity of the well the casing above must be at least 1150 m in scenario 2 and 1050 m in scenario 1.

Overpressure, i.e. pressure above hydrostatic pressure, have not been included as design conditions. Overpressure gas pockets, which may be expected when drilling for oil and gas, are rare or unknown in high enthalpy resources. Self-sealing, related to difference in solvability of the fluid around the critical point, is possible and such sealing may be a pressure barrier which might result in overpressure. Possible overpressure will be observed during drilling. The production casing is likely to be 3000 m or deeper, to seal out colder aquifers, and will be installed before drilling into the zone where overpressure might be. The pressure containment of the well is therefore considerably higher than the down hole pressure indicated in the scenarios described above and able to contain considerable overpressure. Overpressure could however be challenging during operation of the well.

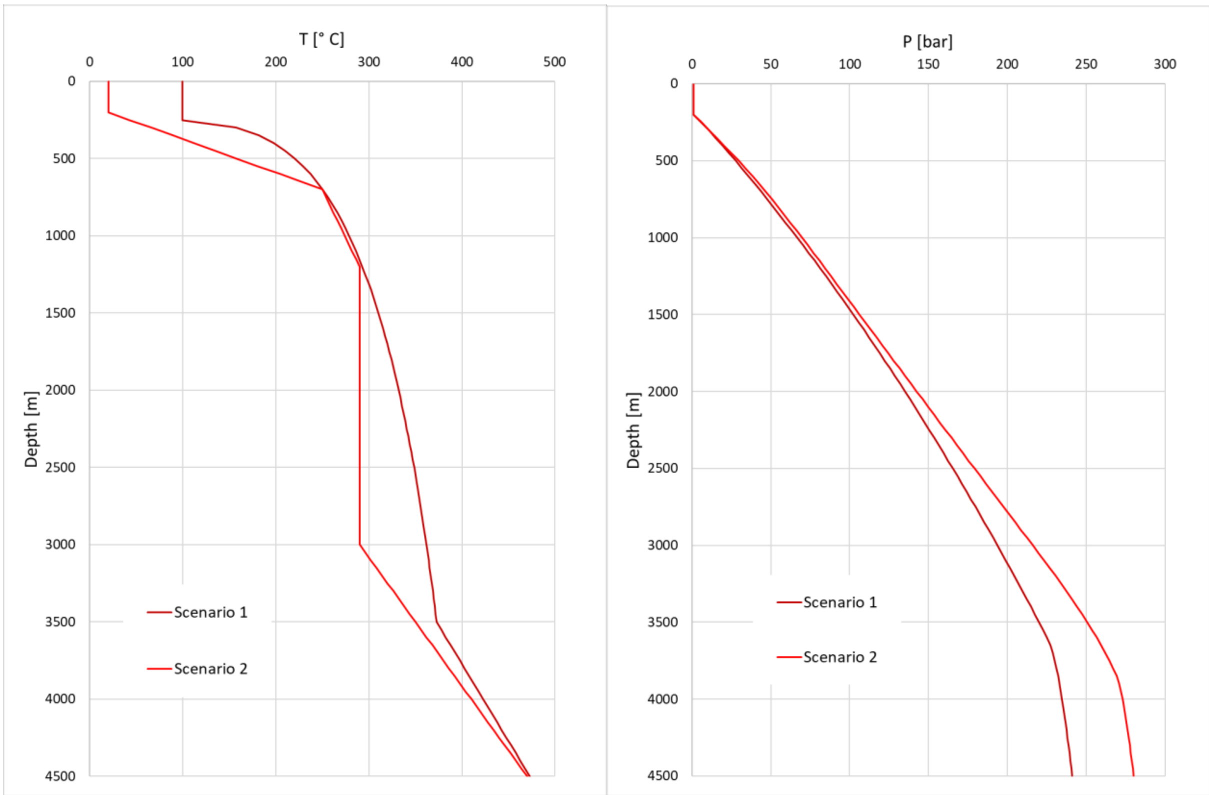

Figure 1: Examples of two scenarios of downhole temperature, on the left, and consequent pressure profiles on the right

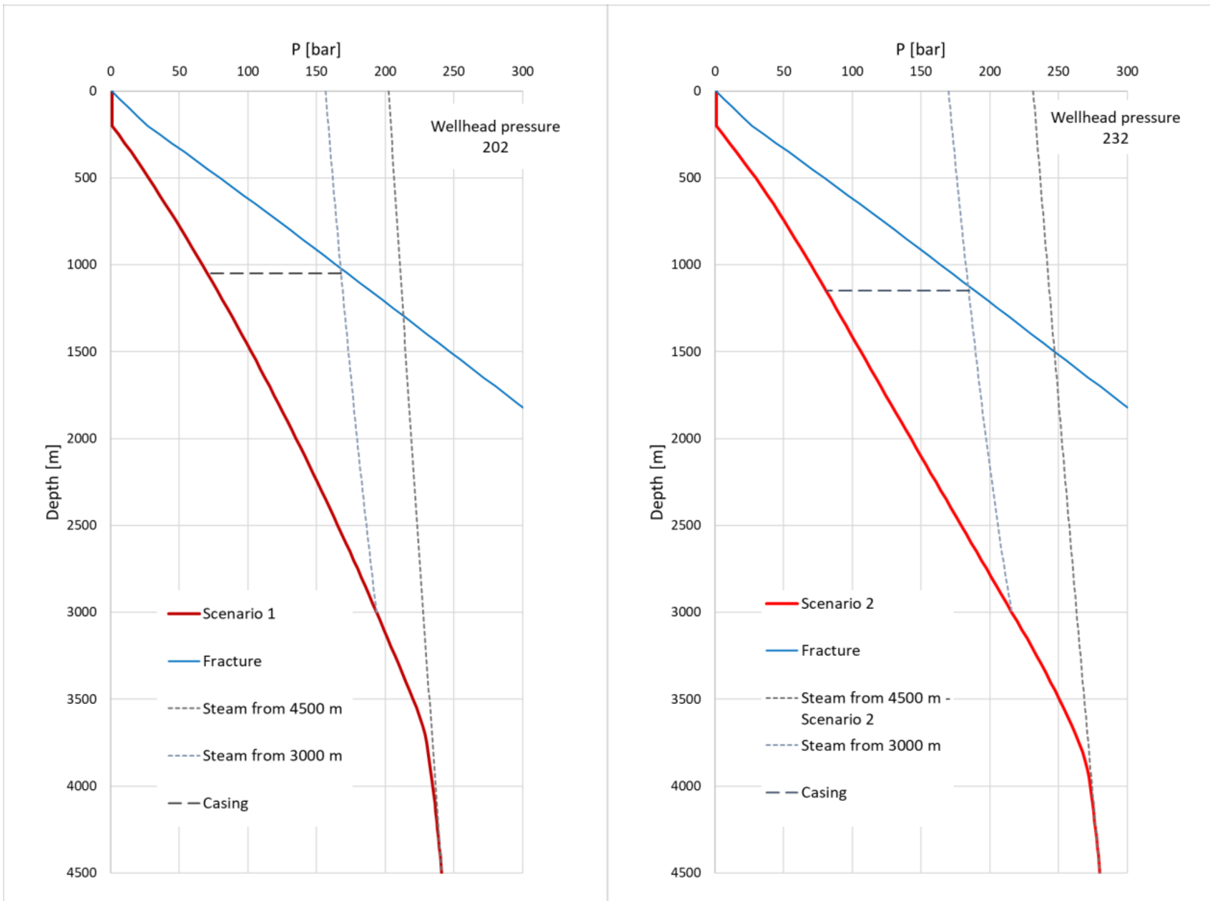

Figure 2: Pressure profiles in well for the two scenarios described in figure 1. Scenario 1 on the left and scenario 2 on the right

4. DESIGN CHALLENGES

The main challenges for drilling superhot wells are discussed in the following.

4.1 High temperature, thermal expansion

The thermal expansion will cause stresses in the casing above the yield point. However, if the casing is properly cementing and the strain will be uniform, the maximum strain will be no more than 0,6% as presented in the Figure below, while the tensile strain of K55 casing material is more than 30%. Despite this, casings have failed because of thermal expansion probably due to one or more of the following reasons:

- Strain is not uniformly distributed
- Strain properties changes during repeated heating – cooling circulation
- Sudden change in temperature, such as when quenching the well, is likely to cause extra load

If a well is kept hot from when its first discharge, thermal expansion is unlikely to cause problem. In practice this may though be difficult.

Casings with connections which allow thermal expansion are being developed and will soon be tested in Iceland. The couplings will be anchored in the cement but the casing can expand. No axial thermal stress will be in such casing string.

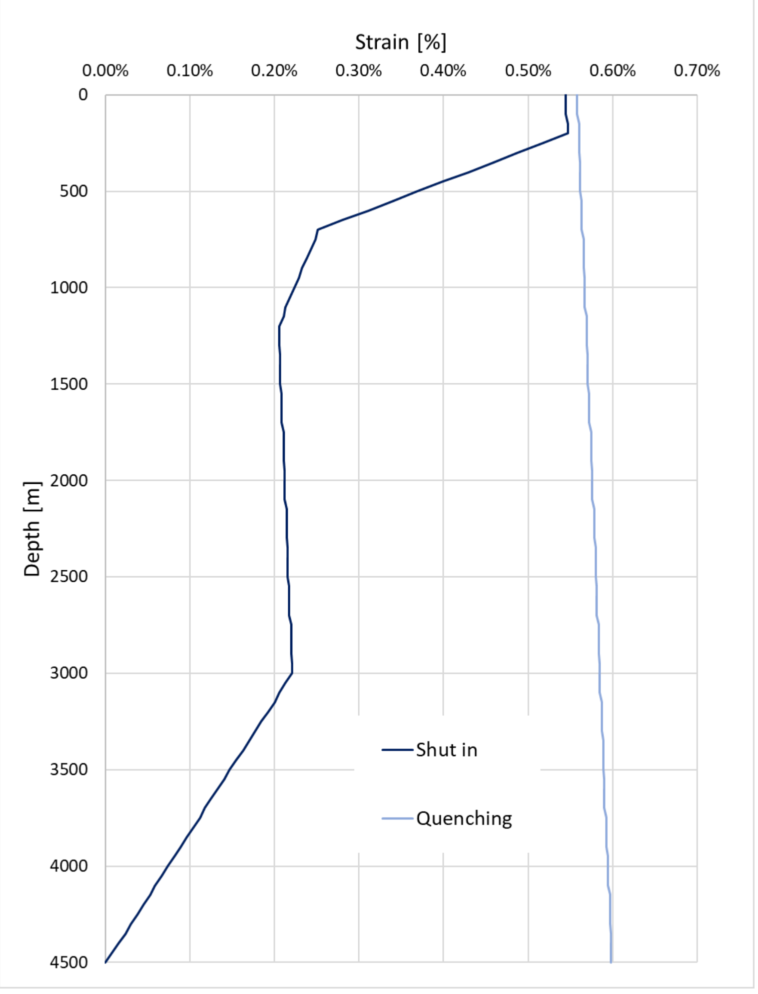

Figure 3: Maximum strain of casing

4.2 P and T at wellhead

It is likely that the wellhead pressure when the well is discharging will be around 100 bar and 350 – 450 °C, depending on the enthalpy of the fluid. The steam will be superheated at this pressure and silica (SiO_2) precipitation is unlikely to cause problems. The wellhead must also be strong enough for the maximum pressure as discussed in clause 3. This could occur when the well is shut in. For scenario 2 this is 232 bar and 440 °C. The wellhead will though cool down in most cases once the well is not discharging and the temperature therefore usually not an issue when the well is shut in.

The Pressure - Temperature rating according ASME B16.5 Class 2500 and Class 1500, material 1.9 is shown in Figure 4 as well as for 14”, T95, 114 lb/ft casing calculated according to ASME B31.1. Maximum strength of presently available master valves is

Class 1500 housing with Class 2500 flanges. The P-T rating for such valves is shown in the graph on Figure 4. The wellhead condition according to scenario 2 is just below the Cl 1500/2500 limit, well above Cl 1500 and below Cl 2500. The scenario 2 wellhead condition is below the 14", T95, 114 lb/ft casing strength with 15% excess allowance although above the casing strength without any excess allowance. This is acceptable as the load is only temporary. From the graph in Figure 4 one can see that if the temperature on the wellhead will be higher than 450 °C the strength of the wellhead will become critical.

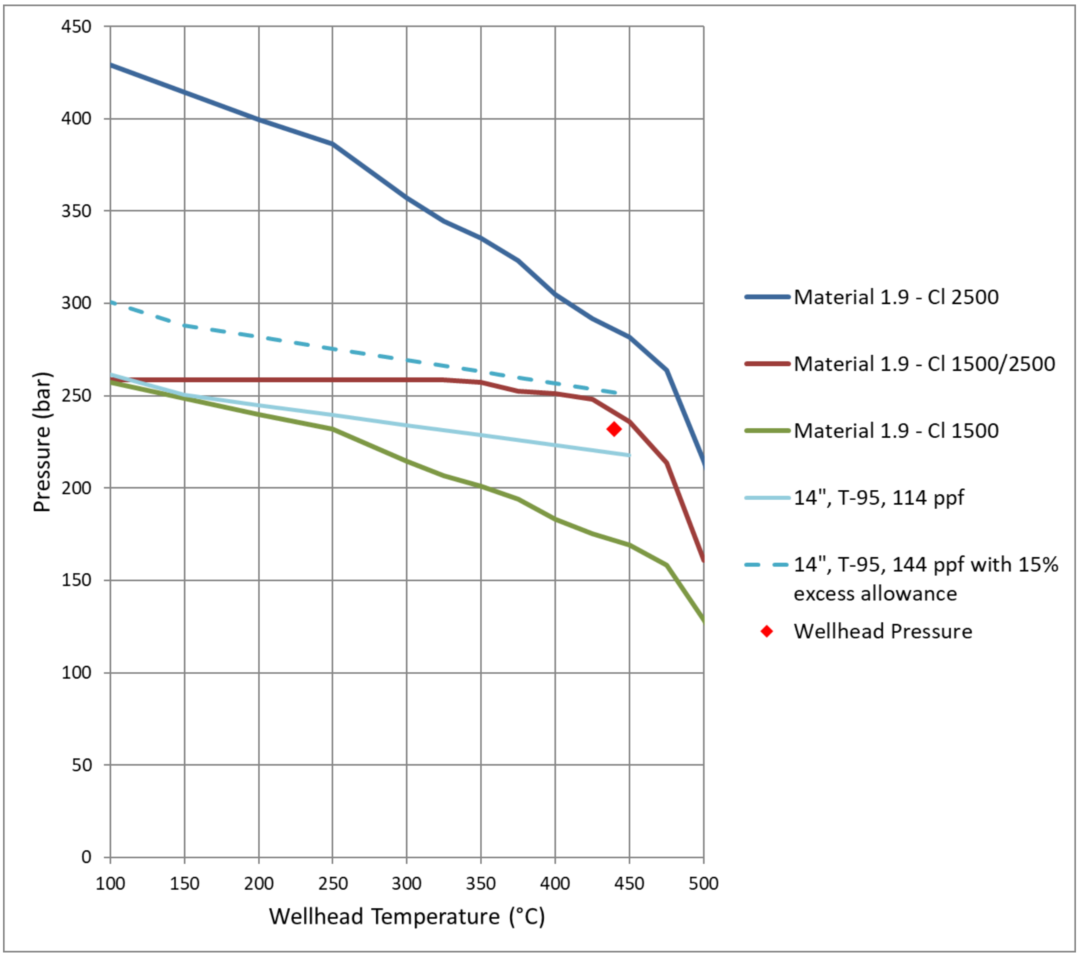

Figure 4: Temperature and Pressure ratings according to ASME B16.5 and ASME B31.1

4.3 Cementing long casing strings.

The casings in a well for superhot fluid can reach down 3000 m. This is three times longer casing compared to most conventional geothermal wells but is not unknown in oil and gas drilling. Good cementing of casings in these superhot wells is however more important than usual in oil and gas wells, and essential if the well is to withstand the high temperature. Any water pocket in annulus between casings will result in casing failure. The casing must be well fixed along its total length for the strain, discussed in clause 4.1 to be uniform.

The design of the cementing and the cementing method used must therefore be selected with the following in mind:

- Good cementing around casing shoe
- Good cementing in the annulus in between casings, no pockets
- No long uncemented parts

The cementing methods which have been used are stage cementing, reverse cementing and tie-back. Cementing tools used in stage cementing in oil and gas drilling, may not be adequate for superhot drilling and must be adapted to the high temperature which the tool may be exposed before cementing. The cementing mixture must also be adapted to the temperature and the time required to pump the large volume of cement.

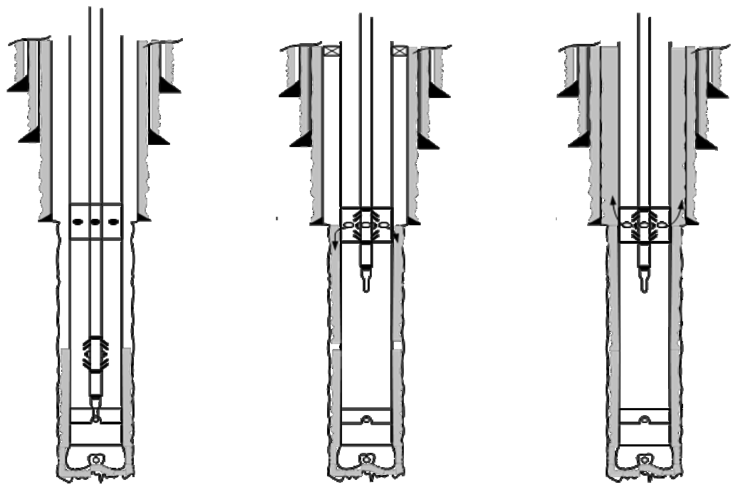

Figure 5: Inner-string stage cementing

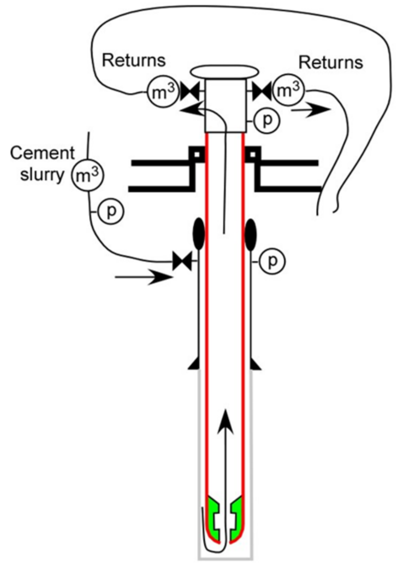

Figure 6: Reverse cementing

4.4 Corrosion

The superheated steam from IDDP 1 was not corrosive and did not seem to damage carbon steel casings. The condensate on the other hand was very corrosive. This caused corrosion during heating up of the well but once it was superheated the corrosion stopped. Example of this can be seen in Figure 5. When the discharge starts corrosion residues from down hole make the steam black as can be seen on the picture on the left. However, after discharging for roughly half an hour the steam became transparent as can be seen on the picture on the right.

This corrosion to be expected during heating up of the well must be dealt with. This can be for example through material selection, cladding or by some type of sacrificial casing design.

Figure 7: Steam from IDDP 1, initial discharge on the left and superheated steam after 30 minutes discharge on the right

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