Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Utilization of Superhot Geothermal Systems – Challenges and Opportunities

Kristinn Ingason, Vilhjalmur Kristjansson

Mannvit, Urðarhvarf 6, 203 Kópavogur, Iceland

kristinn@mannvit.is

Keywords: IDDP-1, IDDP-2, superheated geothermal steam, challenges, lessons learned

ABSTRACT

The IDDP project has been ongoing for 20 years. The history of the project has been described in several papers. From engineering point of view one of the most challenging issue in the beginning of the project was the lack of data to determine the design conditions. Data accumulated during drilling and of IDDP-1 and IDDP-2 and information collected throughout various flow tests of IDDP-1 have changed that and added to the knowledge of which downhole conditions may be expected when drilling into superhot geothermal systems. As the design conditions have been better identified, the plans for drilling into superhot geothermal systems and utilization of the fluid have been improved. The lessons learned from the IDDP project from engineering perspective are discussed and the opportunities for utilizing the fluid from superhot geothermal system are outlined from engineering, economic and environmental point of view. The IDDP project has revealed several challenges which must be solved before this utilization can be considered commercial. These challenges are addressed and discussed.

1. INTRODUCTION

The Iceland Deep Drilling Project, IDDP, started in the year 2000 when the consortium of three Icelandic energy companies and the National Energy Authority of Iceland was founded. The preparation of drilling 2-5 km deep well into a high-temperature hydrothermal system in order to reach 400-600 °C hot fluid was started, and a feasibility report was completed in 2003. The feasibility report was in three parts: Part 1 on geosciences and site selection, Part 2 on drilling techniques, and Part 3 on fluid handling and evaluation. The feasibility report reflects how uncertain the design conditions were. It was concluded that a well could in all likelihood be drilled safely to intersect supercritical temperatures. The major goals of the drilling were a) to allow fluid to be produced and b) to meet the scientific goals by continuously coring where high temperatures were expected. The fluid handling and evaluation discussed how the properties of the fluid would be identified. A plan was outlined where a flow test would be through a narrow replaceable liner or pipe inserted in the well. The pipe would serve to protect the casing from corrosion and scale deposition during initial testing.

The plans outlined in the feasibility study were modified somewhat before drilling IDDP-1. Continuous coring was abandoned and replaced with spot coring which however was not successful in IDDP-1. Spot coring was not either successful in when drilling IDDP-2, but over 20 m of cores were successfully taken at well bottom and indications of supercritical fluid found. The pipe concept was likewise abandoned, and the flow test conducted in a manner as described in previously published papers (Ingason et al 2010 and Ingason et al 2014).

Following the drilling of IDDP-1 and IDDP-2 and discharging of IDDP-1, design conditions are much better known than when the feasibility report was made in 2003. The drilling technology used has in general terms proven to be adequate for the drilling. The water used during drilling kept the drill bit cool enough to drill into magma and the hot formation was fractured during and after drilling as indicated by large losses of circulation water. When the well had heated up during discharging the fluid was neither corrosive nor caused scale deposition provided the pressure and temperature were adequate. The steam condensate was however very aggressive and caused corrosion during heating up and if the well was shut in. The power generating process must be adapted to the chemical properties of the fluid.

IDDP-1 and IDDP-2 revealed several challenges which must be solved before power plant utilizing superhot geothermal resource can be considered commercial. Some of these are discussed in the following.

2. OPPORTUNITIES

The opportunities related to drilling for and utilizing superhot geothermal fluid are higher output of the production wells and consequently fewer wells which needs to be drilled. A comparison indicates that if the drilling of wells into superhot reservoir will be successful the number of wells may be reduced by almost 80%. Even though the superhot wells are more expensive compared to conventional geothermal wells, the total drilling cost is considerably reduced. Not only production wells will be fewer but also injection wells, as the steam contains no liquid. Fewer wells will not only lead to cost savings but also the footprint of the power plant will be less which generally is considered an advantage with respect to environmental impact.

Obvious opportunities are related to construct a superhot geothermal power plant as an extension to an existing conventional geothermal power plant. Wells would be drilled deeper into the geothermal reservoir and cased down below the existing production zone. The size of the reservoir would thus be increased by deepening it. Existing infrastructure such as roads and connection to the electrical grid would be used, making the power plant even more attractive.

When producing electrical power from heat, the efficiency of the power generating process will be higher the higher the temperature of the heat source. Utilizing superhot geothermal reservoir means therefore the geothermal resource is used more efficiently compared to conventional and colder one.

Discharge testing of IDDP-1 confirmed that the output of wells drilled into superhot reservoir can be multiple output of conventional wells. Comparison of conventional geothermal power plant utilizing hydrothermal resource and a power plant utilizing superhot fluid indicates the latter may be more economically feasible (Ingason and Sæther 2018) and the levelized cost of electricity (LCOE) for the two types of power plants indicates that the superhot utilization has a saving potential of 18%.

3. DRY STEAM PROPERTIES - PROCESS

The main chemical properties of the fluid from IDDP-1 are presented in Table 1. The chemistry is not very different from fluid chemistry in some other geothermal wells and the gas content is even lower than usual. However, while the steam from conventional geothermal well is wet saturated, the steam from IDDP-1 was superheated. This difference has the following consequences:

- Silica will precipitate when the pressure and temperature drop
- The steam condensate will be very aggressive
- The geothermal superheated steam may attack the metals causing corrosion, embrittlement or other damages

The properties of the steam described above makes it necessary to treat the steam before it can be utilized for power generation using the technology presently available. This treatment will, however, be down-stream of the wellhead i.e. the wellhead must withstand the untreated fluid.

Table 1: Main chemical properties of the fluid from IDDP-1 (Hauksson et al, 2014)

Property	Value	Unit/Remarks
pH	2.62	Condensate at 240-270°C
CO_2	732	mg/kg
H_2S	339	mg/kg
Cl^-	93	mg/kg
F^-	5	mg/kg
H_2	10	mg/kg
TSS	94	mg/kg, mainly SiO_2 and S
Fe	8	mg/kg
B	1	mg/kg
NH_3	0.14	mg/kg

The power generating process suggested for the utilization of superhot wells requires that the steam pressure will be lowered at the well pads. Condensate will be used to wash out the SiO_2, which will precipitate when the pressure is lowered, and through NaOH injection HCl and other acids will be neutralized. This wet scrubbing method is the result of experiments carried out during discharging of IDDP-1. After this treatment of the steam, it has similar properties as conventional geothermal steam and can be utilized for electrical generation in a comparable way as in a conventional geothermal power plant. Figure 1 shows a flow diagram of this process.

Wet scrubbing will, however, reduce the excergy of the steam the efficiency of the cycle is not optimized. Development of power generating processes where the steam is used without wet scrubbing, can increase the electrical power generated still more. This has been discussed by Saevarsdottir et al, 2015.

The fluid from the well will be superheated steam at high pressure. The pressure is lowered before the wet scrubbing. The SiO_2, dissolved in the high-pressure steam, precipitates at the lower pressure. The scrubbing of the steam takes place in two steps. In the first step the steam is de-superheated and the SiO_2 washed out of it and in the second stage HCl and other acids are neutralized by spraying NaOH solution into the wet steam. Condensate is used for the de-superheating and part of it will evaporate, adding to the total flow of the steam. The quality of the steam, flowing from the wet scrubbing system, will potentially be approximately 98%.

Wet scrubbing systems will be located at each well pad. The fluid flowing from the well pads will be of similar properties as conventional geothermal steam, but with less water content. This steam will be piped from the well pads to the power station and utilized in a comparable way as in conventional geothermal power plant.

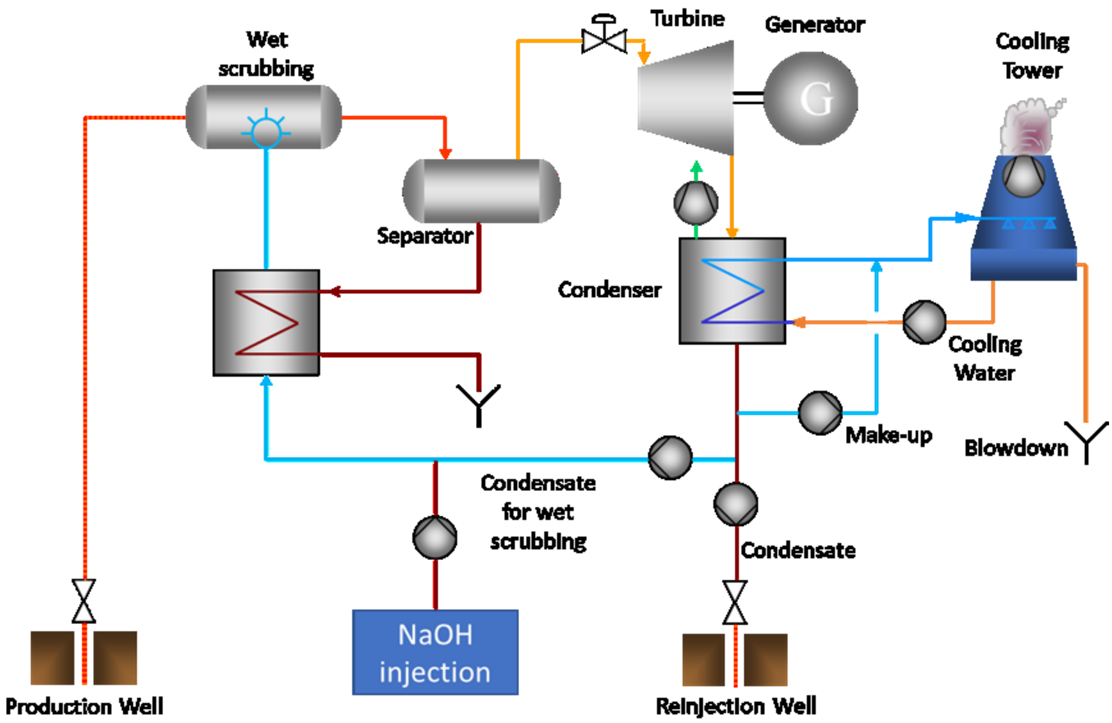

Figure 1: Power generating process for utilizing superhot fluid.

4. CORROSION – EROSION

Various difficulties related to corrosion and erosion were one of many challenges during the flow testing of IDDP-1. Silica precipitation in geothermal environment is mainly amorphous and depends on the fluid temperature and pressure. The steam at the wellhead of IDDP-1 was up to 450 °C hot and the pressure 140 bar. The maximum solubility of amorphous SiO_2 at these conditions in pure steam is at least 100 mg/kg (Hauksson et al, 2014).

Silica precipitation experiments were done at various pressure drops in 2012 during the discharge of the IDDP-1 well. The precipitation rate of SiO_2 was negligible when the pressure was over 80 bar but when pressure got below 80 bar, silica started to precipitate more rapidly, and the highest precipitation rate was experienced when fluid was depressurized down to 40-50 bar (Hauksson et al, 2013). The precipitation rate has reduced considerably when the pressure was below 20 bar.

SiO_2 caused erosion damages during some phases of the discharge of IDDP-1. The erosion was related to the condition of the flow i.e. low pressure when SiO_2 had precipitated from the steam and high velocity. At higher pressure no erosion was observed.

The condensate of the steam in IDDP-1 was aggressive and some parts of the wells were subject to the condensate during heating up of the well and during intervals when the flow from the well was stopped. This applies for the perforated liner and debris from it were collected from the wellhead after a discharge test in August 2011. This was also observed in some nozzles on wellhead, which corroded heavily due to external cooling causing steam to condense. It is emphasized that the following discussion and corrosion damages were partly occurring during heating up of the well. During heating up of the well, the liner was immersed in liquid fluid which eventually heated up during start-up of the well.

The production liner probably corroded severely during the heating up of the well in 2011, this was confirmed by debris retrieved from the wellhead during discharge test in August 2011 (Ingason et al, 2014). Furthermore, the API K55 casing material seemed to be susceptible for hydrogen damage at high temperatures and high partial pressure of hydrogen experienced at IDDP-1.

Early 2016, three and a half year after the IDDP-1 well was quenched and killed in 2012, samples from the top 8 m and some steel fragments from the downhole casing were retrieved for analysis. The production casing, which is made of API K55 carbon steel, at the wellhead turned out to be heavily corroded 500 mm from the top as shown Figure 2.

Analysis of the API K55 carbon steel fragments revealed pitting corrosion, cracks and fissures parallel to the surface of the API K55 samples. The fractography of the cracks indicated sulphide stress corrosion cracking (Karlsdóttir et al, 2016). This corrosion form has though probably progressed during heating up of the well while liner and most of casing were immersed in liquid fluid. This analysis is therefore not representative for superheated conditions only.

All the API K55 samples of the production casing in the corroded area revealed pitting corrosion and suffered fissures or large horizontal cracks, especially at the grain boundaries. The samples from the anchor casing, which made of API T95, were less affected but still had some fissures and cracks. Most probably, the cracking at the grain boundaries is due to decarburization [5] i.e. hydrogen attacking the carbon at the grain boundaries. The higher Cr-Mo steel, T95 was less affected by the high temperature hydrogen attack in comparison with the K55.

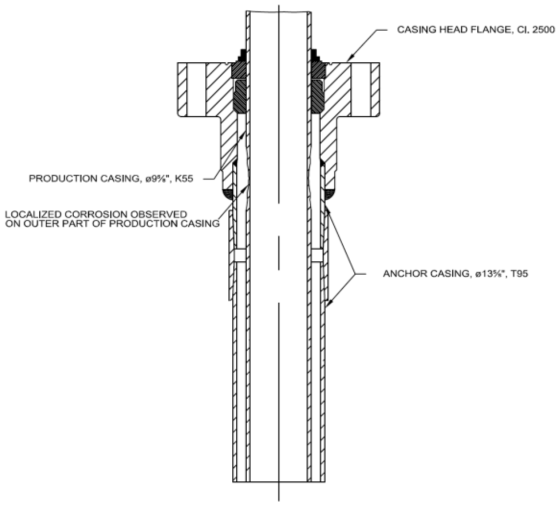

Figure 2 Corrosion damages observed at the top of the production casing

5. WELL DESIGN

The most critical component in a power plant utilizing superhot geothermal reservoir are the wells. The wells be designed to reach down into the superhot reservoir and to withstand the high temperature and aggressive chemistry of the fluid and the drilling must be conducted in a save way. Among the challenges to be addressed are:

- High temperature which causes thermal expansion and high mechanical load
- Corrosion and erosion, steam condensate is very aggressive and if SiO_2 precipitates from the steam it may cause erosion. Although the steam itself is not aggressive, the condensate is aggressive and the steam will condensate during heating up of the well and if the well is shut in.
- Cementing long casing strings has proven to be challenging. It is important to have good cement at the casing shoe and in annulus between casings and it is also important to fix the casing and not have uncemented sections.
- Pressure and temperature at wellhead is considerably higher compared with conventional geothermal wells.

These challenges are discussed in Ingason and Sigurdsson 2020.

A clear example how the corrosion is related to the steam condensate can be seen in Figure 2 below. 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.

Figure 3: Steam from IDDP 1, beginning of discharge on the left and superheated steam after 30 minutes discharge on the right

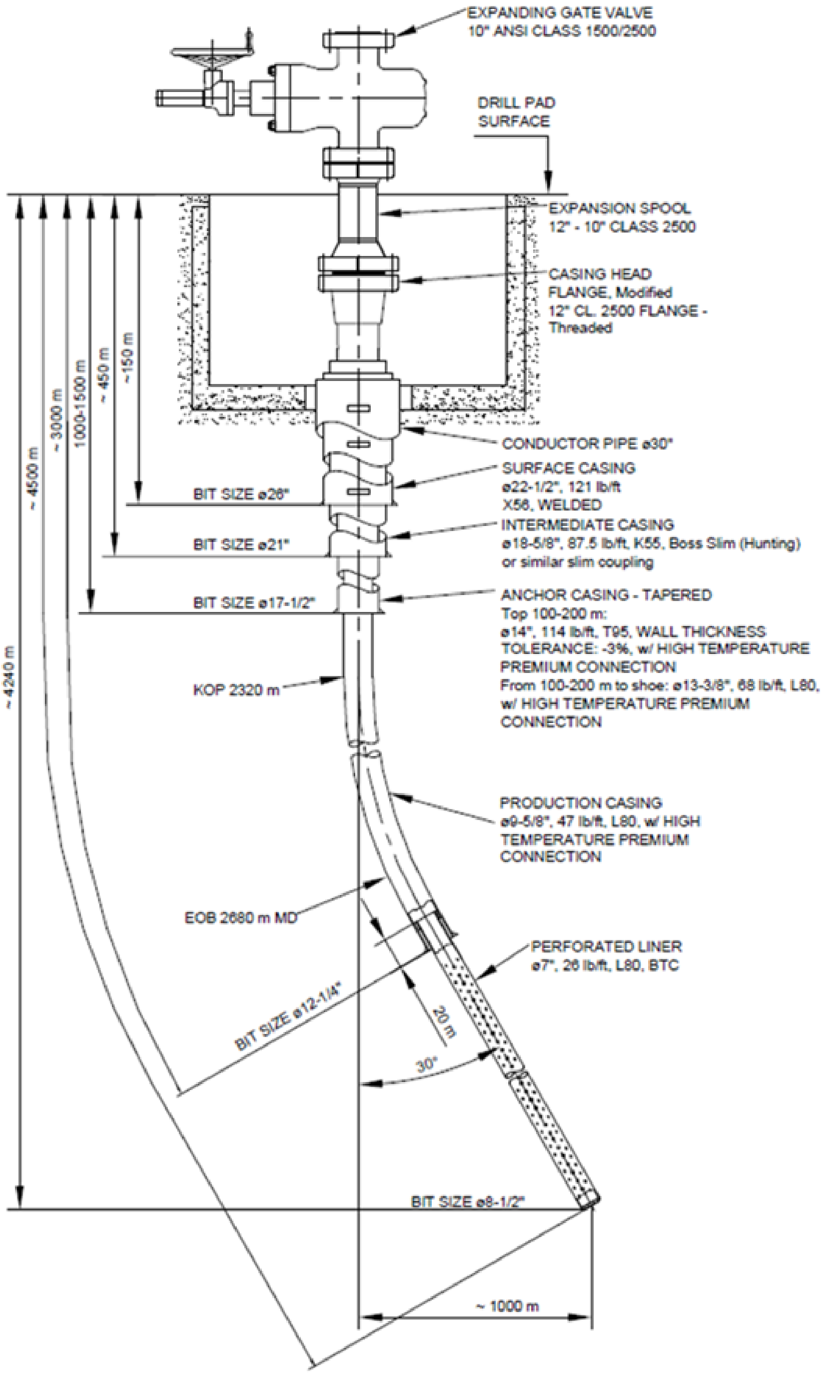

Figure 4: Possible design of well drilled into superhot reservoir.

6. VALVES

Experience from utilization of conventional wells has been established through decades and modern setups reflect the knowledge gained for instance in the choice of valve types and material. In case of failure of valves or other wellhead equipment the consequences are usually to shut in the well. The necessity to shut in a well is though not always due to complete failure but often rather because of the need for service of equipment or operational reasons. For conventional wells an occasional shut in during the lifetime of a well is acceptable.

Various valve types of different sizes are commonly used on wellheads of conventional wells. Their role can be said to be equally important (i.e. there are no unnecessary valves installed) though the master valves are the one that ensure the integrity of the well.

Dedicated valves are installed for opening and closing for flow from wells. During opening/closing the flow is throttled and internal mechanism of the valves vulnerable to erosion and/or cavitation, depending on the state of the fluid. Large bore valves with conventional gears and actuators have longer opening/closing time and hence subject to throttled conditions for longer periods than smaller bore valves. Figure 5 shows an extreme case of damage on a valve used to open for flow on the IDDP-1 well.

Figure 5 Heavily damaged seat on a 10", Cl1500 gate valve used for opening/closing of IDDP-1 in one of the discharge phases.

Valves used to regulate, or limit flow are in constant throttled state. They are prone to be subject to service and maintenance with regular intervals. Small valves used for sampling and pressure monitoring risk to become clogged or seized as they can act as a "pocket" for debris collection. There is also the hazard of condensate build up due to a "dead end".

Reports of total failure of well master valves (inoperable valves leading to out-of-control situations) are nearly unknown and failure of master valves leading to shut in of wells or choking (controlled situation) are fortunately rare.

Master valves on high temperature wells are most often of the expanding gate design. Exception form this can be found in Larderello, Italy, where flexible wedge master valves are used in dry steam wells. Some of the advantages of expanding gate valves are:

- Designed for high pressure, up to Cl 2500, though size limited
- Full-bore, through conduit allowing drill bit to run through the valve and minimum flow turbulences and therefore minimum scaling
- Sealing both upstream and downstream therefore more tightness of valves
- Sealing surfaces are protected as the sealing is active both when the valve is closed and open
- Sealing of the valve house when valve is open, therefore isolated from fluid in well, particularly drilling fluid
- Maintenance, such as on gland seal, can be carried out when valve is inline and in operation, i.e. removal of valve not necessary

Challenges in design of master valves for superhot wells remain. Valves of ø10" diameter, which are required as master valves on such wells, are presently only available in ANSI Class 1500 body with welded Class 2500 flanges. It is important to have the master valve as full Class 2500.

Material selection of different components of the valve should be carefully selected. Relatively minor change of design of expanding valve, which would eliminate problems caused by different temperature in the master valves and associated difference in thermal expansion, could be to leave out the sealing when the valve is open.

7. WELLHEAD CONCEPT

Discharge testing of IDDP-1 revealed the necessity of a double discharge system in the event of maintenance of the main discharge system. The secondary discharge pipeline does not have to be the same size as the main pipe. It can be smaller but still allow the well to discharge on a restricted flow to keep it in hot condition.

Design and arrangement of wellheads for superhot wells should be based on the following condition:

- Pressure at wellhead during discharging must be high enough to prevent SiO_2 precipitation
- Valves shall be installed in series, the valve downstream will normally be operated while the valve upstream will be redundant
- When possible use smaller diameter valves in parallel rather than one large valve. This is based on the experience that large valves are more difficult to operate and are more prone to erosion. Preferable maximum size of valves is 6".
- Ends such as nozzles which may be cooled enough for the steam to condensate during discharging, should be avoided.
- Once the well starts to flow it should preferably not be shut in. By installing two discharge pipelines the likelihood of having to shut-in the well is reduced.
- Valves and pipelines can mostly be of carbon steel internally cladded by stainless steel or Inconel for corrosion resistance
- Valves are stop valves, not for controlling of flow. Orifices shall be used for controlling the flow.

Compensation with regards to well head rise should be implemented for example a constant force supports for pipes connected to the wellhead.

Pressure and temperature sensors were prone to malfunction during the discharge phases of IDDP-1, something that can be related strictly to the harsh environment. Wellhead conditions must constantly be observed, both during flow and no flow situations. It is important to locate pressure sensors in each pressure step of the discharge system and the collector pipe system from the well.

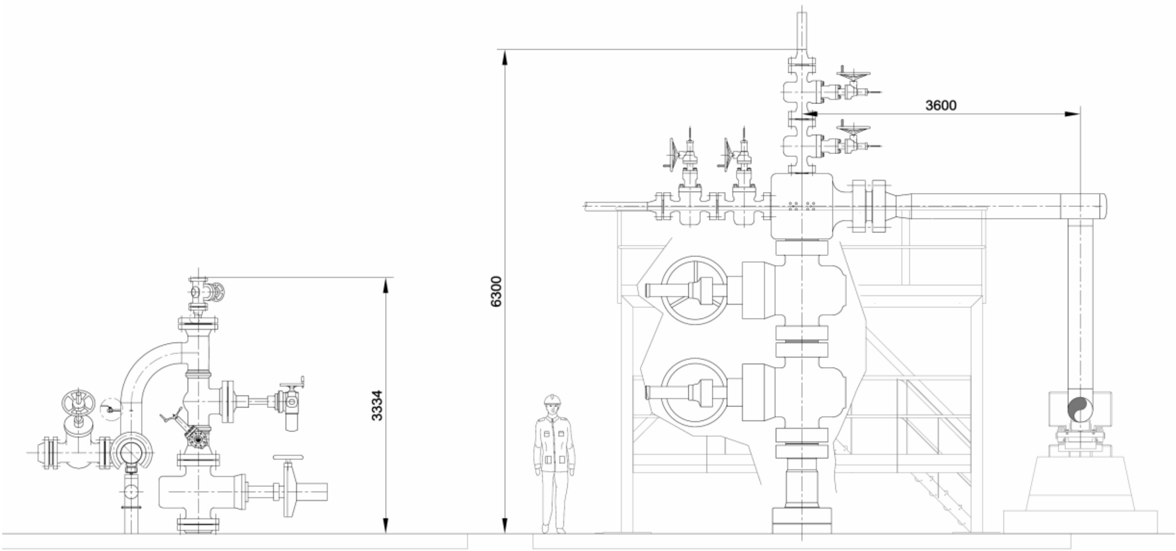

Figure 6 Comparison of well head for conventional well (left) and well head for Superhot well (right)

8. CLADDING

The wellhead and master valves of IDDP-1 were cladded by welding AISI 309. Cladding of this type has been used effectively as an example in Lardarello, Italy, for corrosion protection in dry wells.

In the in-situ corrosion testing at the wellhead of IDDP-1, all the alloys were prone to pitting. The alloys that had Mo ≤ 3.5 wt/wt% were also prone to SSC. Due to low corrosion rate and that all the alloys tested suffered localized damage, carbon steel is a logical option for casing for economic reasons. If condensation occurs however, corrosion resistant alloys as base material or carbon steel cladded with corrosion resistant alloy would reduce the corrosion rate significantly. If more corrosion resistant alloys will be selected as a base or cladding material, molybdenum content should preferably be higher than 3.5 wt/wt%.

The corrosion behavior of the alloys in superheated geothermal system need to be studied further to understand and clarify which alloys are most suitable. The testing in IDDP-1 was not continuous (two test batches, test chamber and silencer) and this interruption may have affected the corrosion forms analyzed after the complete corrosion testing.

In future IDDP wells, Inconel 625 has been suggested as cladding material for material and equipment which may be exposed to condensate at the wellhead. In the corrosion coupon and U-bend testing in IDDP-1 at 350-360 °C at 12-13 bars, it was concluded that alloy Inconel 625 suffered localized damage, possibly initiating under silica deposits or at grain boundaries (all alloys tested were apparently prone to localized damage). The pit penetration depth in Inconel 625 in the in-situ testing at 350-360 °C at 12-13 bar was apparently 5-10 µm after 113 day exposure. Furthermore, it was concluded that the alloy was not susceptible for hydrogen embrittlement (Karlsdottir et al, 2015).

Various testing in non-geothermal supercritical water have been conducted for Inconel 625. Testing in supercritical waters in slightly oxidizing or reducing environment (not geothermal though) indicates that nickel-based alloys are less susceptible than 316L austenitic stainless steel to hydrogen damage, Fujisawa et al, 2006.

REFERENCES

Albertsson, A., Bjarnason, J. O., Gunnarsson, T., Ballzus, C., Ingason, K.: IDDP Feasibility Report, Part III, Fluid Handling and Evaluation, May 2003.

Fridleifsson, G. O., Armannsson, A., Arnason, K., Bjarnason, I. Th., Gislason, G.: IDDP Feasibility Report, Part I, Geoscience – Site selection, May 2003.

Hauksson, T., Markusson, S.H.: Silica in superheated steam of the IDDP-1 exploratory geothermal well in Krafla, Landsvirkjun, November 2013.

Hauksson, T., Markusson, S.H., Einarsson, K., Karlsdottir, S.N., Einarsson, A., Moller, A., Sigmarsson, T.:Pilot testing of handling the fluids from the IDDP-1 exploratory geothermal well, Krafla, Iceland, Geothermics 49, 2014, pp 76 – 82.

Ingason, K., Kristjánsson, V., Einarsson, K.: Design and development of the discharge system of IDDP-1". *Geothermics* 49, 58–65 (2014).

Ingason, K., Sæther, S.: Geothermal Comparison Study, *GRC Transactions*, Vol. 42, 2018

Ingason, K., and Sigurdsson Th.: Design of Super hot Wells, *Proceedings:* World Geothermal Congress 2020 Reykjavik, Iceland, April 26 – May 22, 2020.

Karlsdottir, S.N., Wallevik, S.O., Ragnarsdottir, K.R., Alexandersson, K.F., Haraldsdottir, H.O., Jonsson, T.: Material Testing and Examination of IDDP-1 well materials – *Technical Report for Landsvirkjun*, Gerosion ehf, 2016.

Karlsdottir, S.N., Ragnarsdottir, K.R., Thorbjornsson, I.O., Einarsson, A.: Corrosion testing in superheated geothermal steam in Iceland, *Geothermics* 53, 2015, pp. 281-290.

R. Fujisawa, K. Nishimura, T. Nishida, M. Sakaihara, Y.Kurata, Y. Watanabe,: Corrosion Behavior of Nickel-Based Alloys and Type 316 Stainless Steel in Slightly Oxidized or Reducing Supercritical Water, *Corrosion*, Vol. 62, No.3, pp 270-274, 2006

Saevarsdottir G., Hjartarson S., Ingason K., Pálsson B., Harvey W.: Utilization of Chloride Bearing High Enthalpy Geothermal Fluid. *Proceedings:* World Geothermal Congress 2015, Melbourne, Australia 19-25 April 2015.

Thorhallsson, S., Matthiasson, M., Gislason, Ingason, K., Palsson, B., Fridleifsson G. O.: IDDP Feasibility Report, Part II, Drilling Technology, May 2003.