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

Estimating Flow Performance of IDDP-2/DEEPEGS Well by Introducing Local Injectivity Indexes for Different Reservoir Depths

Sturla Sæther

Equinor ASA, Arkitekt Ebbels veg 10, 7053 Ranheim, Norway

stusa@equinor.com

Keywords: IDDP-2, supercritical, geothermal, well flow, injectivity index

ABSTRACT

The goal of the Iceland Deep Drilling Project (IDDP) is to get appropriate understanding of supercritical reservoirs with ultra high temperatures (400-550 °C). It is a huge potential of increasing the power output from one geothermal well in such reservoirs. There is always very interesting to know the prognosis for production potential and the energy content of hot producing wells in geothermal industry. Injectivity tests on cold wells are normally performed to get indications of the production potential. Despite the fact that data acquisition and stimulation activities of IDDP-2/DEEPEGS well on Reykjanes have met several challenges, a significant amount of valuable data are still collected. These data include several fixed-rate injection tests with combined pressure and temperature measurements, spinner log runs, water table measurements and temperature survey under shut in condition. The injectivity index provides an overall representation of the total well response and will normally not indicate zonal potential or contribution from various feed zones. This work uses existing data as temperature, pressure, and different flow rates during injectivity tests to point out local injectivity indexes. The fact that the pressure inside the well is different during the different injection rates are used in the prediction. The local injectivity indexes are used to predict the potential for hot production from the different production zones of the IDDP-2/DEEPEGS well.

1. INTRODUCTION

Geothermal energy is renewable with a huge potential for power production. The investment costs in an early phase of a project are relatively high, and this increase the risk in geothermal power production compared to more predictable investment costs for solar and wind projects. The latter have improved a lot in the last years with respect to reduced Levelized Cost Of Electricity (LCOE). State of the art of geothermal power production has not seen this improvement in cost reductions. However, geothermal energy with ultra high temperature (400-550 °C) reservoirs has a very high potential to improve power output from each well and thereby reduce investments costs. Equinor has in the last years been investigating the potential for geothermal energy for ultra high temperature reservoirs together with Icelandic and EU partners. Equinor call the ultra high temperature concept for GeoMagma. The potential for such reservoirs is very huge, but there are some challenges with respect to well design and operation of equipment at very high temperatures. Equinor has participated in the Iceland Deep Drilling Project (IDDP) to investigate and learn more about ultra high temperature geothermal reservoirs. Equinor is also a partner in "Deployment of deep enhanced geothermal systems for sustainable energy business, DEEPEGS" which is an EU Horizon2020 project.

The main goal of this paper is to point out the potential well production from each reservoir zones of the IDDP-2/DEEPEGS project drilled at Reykjanes in Iceland in 2016-2017. The well has still not been started due to some challenges with the production casing. More information and the main goals of the IDDP for investigating geothermal system at supercritical conditions can be found in Friðleifsson et al. (2005).

The flow potential from different main production zones and contribution to the total flow of the hot IDDP-2/DEEPEGS well is described in this paper. It is important to analyse the well and how the different production zones most probably will produce at different loads of the well. It is important to point out and predict the potential for geofluid production flow from the lowermost part of the reservoir which is proved to be at supercritical conditions.

The IDDP project has been a world leading project in investigating high temperature geothermal reservoirs. A lot of information can be achieved from the project with respect to new understanding and the challenges to get the concept for ultra high temperatures of geothermal systems up and running (Friðleifsson et al., 2014a, 2014b). More details about the IDDP-2 reservoir and site conditions can be found in Friðleifsson and Elders (2017).

The IDDP-2/DEEPEGS well has the following main data:

- Anchor/production casing down to 3000 meters. Diameter Ø 9 5/6".
    - Sacrificial production casing 0-1300 meters depth. Diameter Ø 7".
- Perforated production liner from 3130 meters down to 4500 meters. Diameter Ø 7".
- Open hole down to 4650 meters Measured Depth (MD).
    - The Total Depth (TD) is 4480 meters.

2. BASELINE DATA AND PREREQUISITE FOR THE ANALYSES

Injectivity tests are normally performed during drilling of geothermal wells to estimate the productivity of the reservoir. Injectivity index (II) is in the IDDP-2 project investigated several times. The main goal for an II is to find an overall production potential for one well, but in this work the II distributed for different zones in one well are focused.

The II investigations are performed by running different amount of injection water into the well, and at the same time measure the pressure at a fixed depth. Iceland GeoSurvey, ÍSOR (Weisenberger et al, 2017) has been responsible for the injectivity test measurements in IDDP-2, and typical data for an injectivity test is given in Figure 1. The blue line shows the pressure during the test with the tool fixed at 2000 meters depth in the well. The highest pressure is at highest injection rate where the water table in the well is rising. The lower pressure plateau is at 30 l/s lower injection rate. The II is calculated by dividing the delta injection water volume by the delta pressure measured at 2000 meters depth for the different injection rates. The overall II for IDDP-2 in this case (January 3rd 2017) is 1,7 l/s bar.

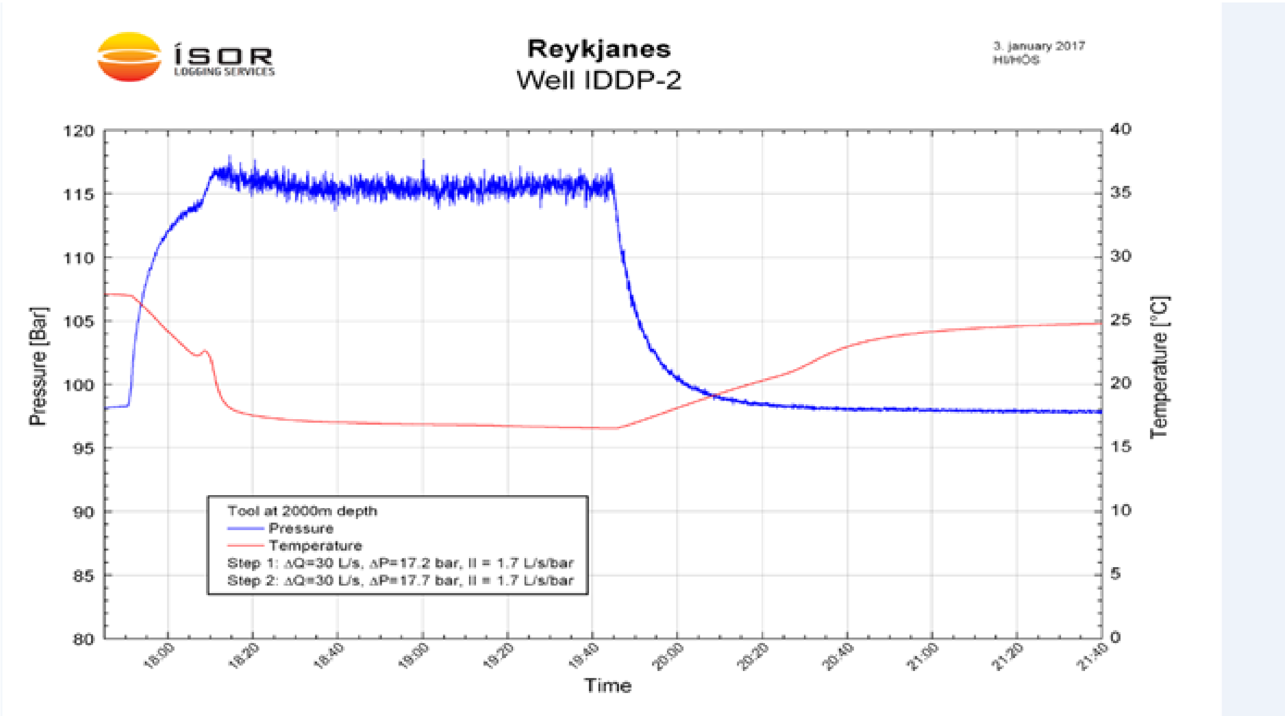

Figure 1: The figure shows pressure and temperature for the injectivity test performed January 3rd 2017. The tool is located at 2000 meters depth (Weisenberger et al, 2017). The difference in injection rate is 30 l/s during the injectivity test.

In order to estimate the local II for a given well more information is required. The information used in this work are:

- Localization of the main potential production zones at different depths by using temperature measurement logs during water injection
- Estimation of reservoir pressure at different depths
- Pressure measurements inside the well for different injection rates

From these types of data, it is possible to establish a local pressure difference between the reservoir and the well pressure at the different potential production zones. Estimation of these pressure differences at the different locations and at different injection rates give the possibility to calculate the local II at each potential production zone. The sum of the local II are summarized to the overall II measured at each test.

The potential main production zones are pointed out by temperature measurements during cold water injection. In Figure 2 the temperature logs for January 3rd 2017 are shown. It can be stated that there are some important turns on the temperature curve at certain locations. To keep these analyses at a simplified level it is found that the most important locations are at 2300, 3400 and 4400 meters depths. The further analyses will use these depths for analyses to state the local II at these locations. The location at 2300 meters depth are special where there is pointed out to be a hole in the production casing. The step in the temperature curve indicates hot reservoir water flowing into the well. See red dotted line in Figure 2. It is found that there is a damage of the casing at this point, and at the moment it is not possible to get into the well below this point with instruments. It is very difficult to exact state the status of the damage. It can be a casing collapse that will give a clear obstruction during flowing of the well, or it can be a rift in the casing allowing that fluid inside the well can interact with the reservoir fluid. In the further analyses it is assumed that the hole in the casing will have no flow obstruction but only fluid interaction between the well and the reservoir. The fluid interaction of the well and the reservoir at 2300 meters depth will depend on the local pressure difference between the well and the reservoir. The local II at 2300 meters depth is calculated based on the temperature step and the rate of reservoir fluid flowing into the well during temperature measurements.

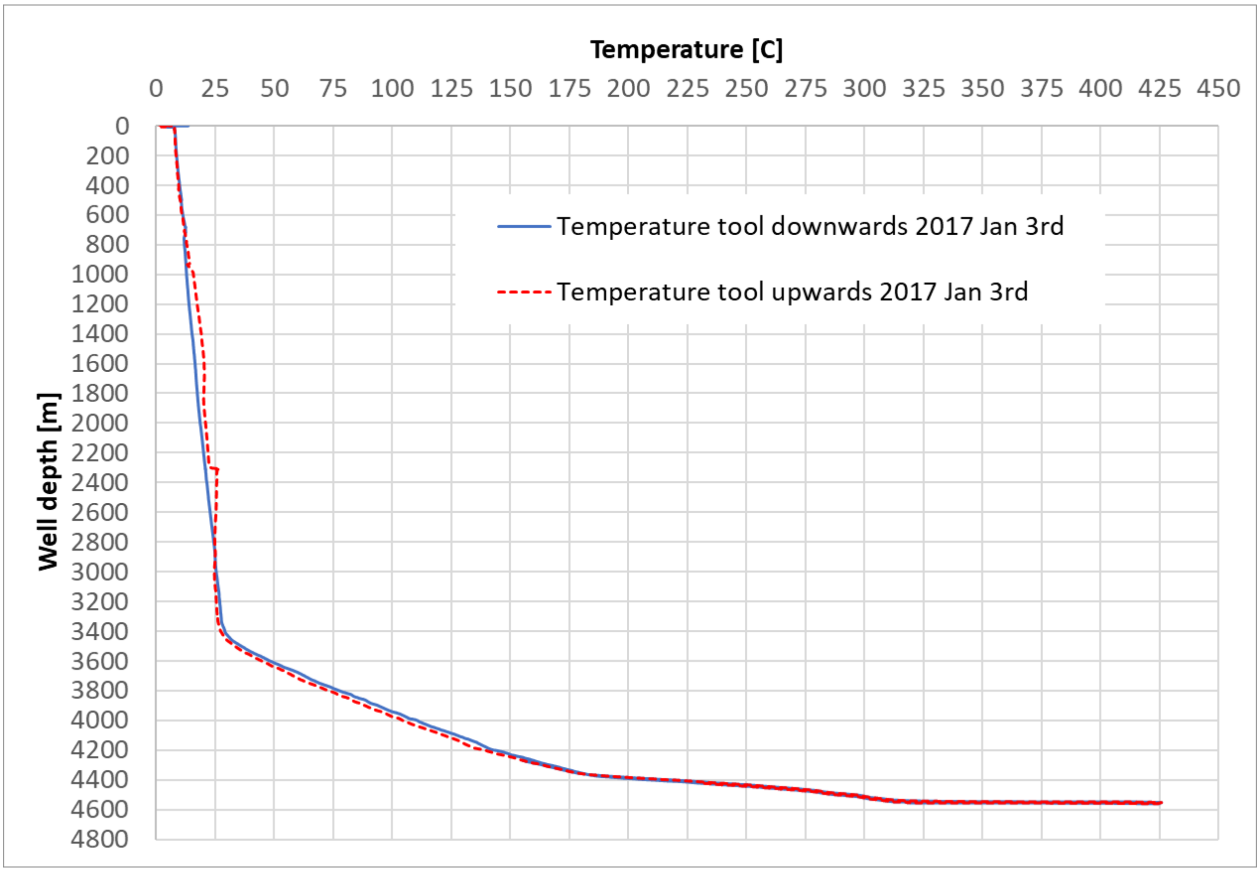

Figure 2: The figure shows the temperature conditions in the well at January 3rd 2017. The temperature is measured downwards with an injection rate of 40 l/s and upwards with an injection rate of 15 l/s. The turns of the temperature indicate locations with relatively high productivity potential (3400 and 4400 meters depth). At 2300 meters depth the step in temperature indicates hole in the casing. Data gathered from Weisenberger et al (2017).

The estimation of the reservoir pressure at Reykjanes peninsula is essential with respect to point out the potential production from the different zones. Reykjanes is an established geothermal area and lot of wells down to 2500 meters are already in operation. The temperature gradients are measured over many years. Based on these data and new temperature predications performed by Hokstad and Tänavsuu-Milkeviciene (2017) a temperature profile of the reservoir is established. See Figure 3. The temperature predications are in the same order as Fridriksson, et al (2015). The temperature prediction is a result of internal work in Equinor and based on experience and methods developed within oil and gas reservoir exploration. The temperature estimation of the Reykjanes reservoir is found in Figure 3 and will be used in the analyses.

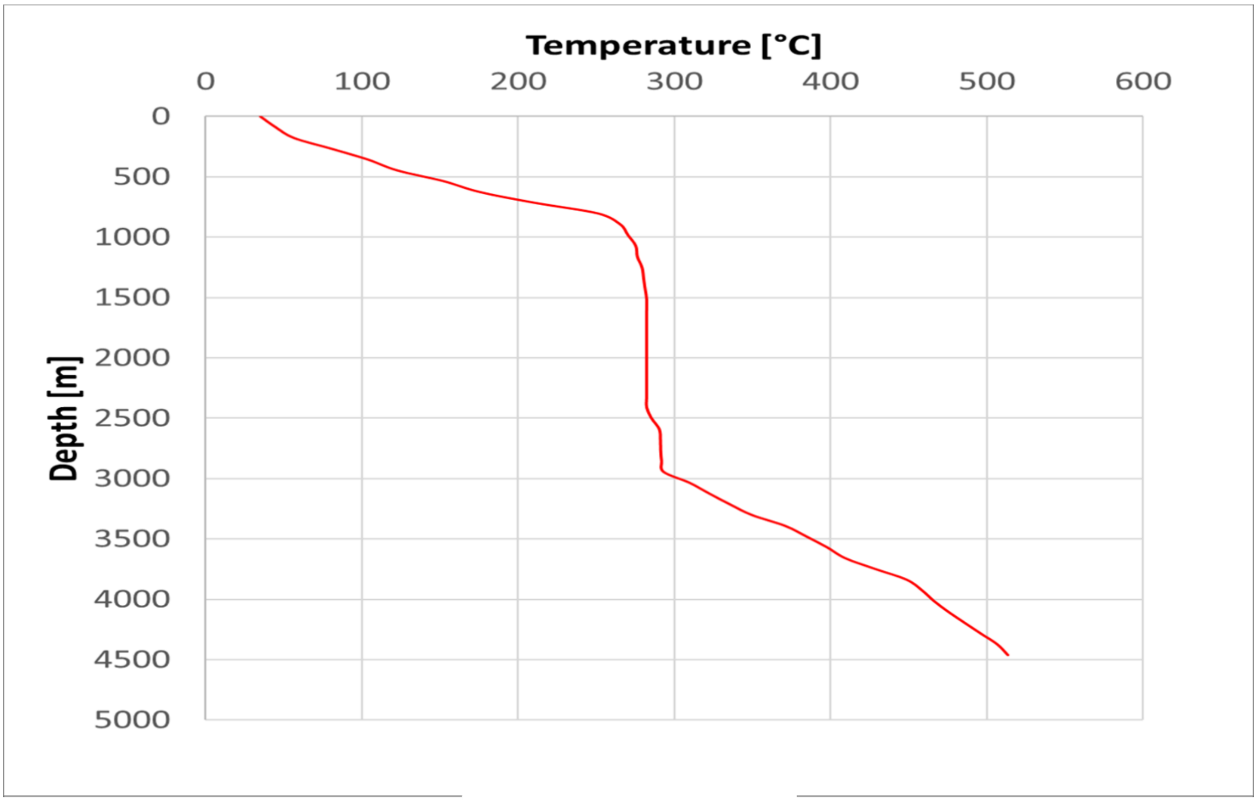

Figure 3: The figure shows the predicted reservoir temperature for the IDDP-2/DEEPEGS reservoir (Hokstad and Tänavsuu-Milkeviciene, 2017). This temperature is the baseline for the reservoir conditions in this study.

3. INVESTIGATING LOCAL INJECTIVITY INDEXES (II) FOR IDDP-2/DEEPEGS WELL

Based on these temperatures and an assumption of hydrostatic reservoir in Reykjanes the reservoir pressures are calculated based on the density of water and a reservoir water table at 540 meters depth. The calculations are simplified by assuming fresh water in this work. In Figure 4 the resulting reservoir pressure is plotted. In addition, the pressure in the well are plotted based on measurements inside the well and corrected for zero water injection. The pressure differences at the potential production zones can be stated based on the pressure profiles for the entire well and reservoir. The pressure differences are given in Figure 4 for injection rate at ZERO. At the location of 2300 meters depth, the difference pressure is minus 28 bar, meaning 28 bar over pressure in the reservoir compared to inside well at this location. The pressure difference at 3400 meters are minus 7 bars and at the lowermost zone at 4400 meters the difference pressure is plus 30 bars. This pressure situation is for ZERO water injection. The mass balance of inflowing waters to the well at 2300 and 3400 meters depth must be fulfilled by the same amount of water flowing into the reservoir at 4400 meters depth.

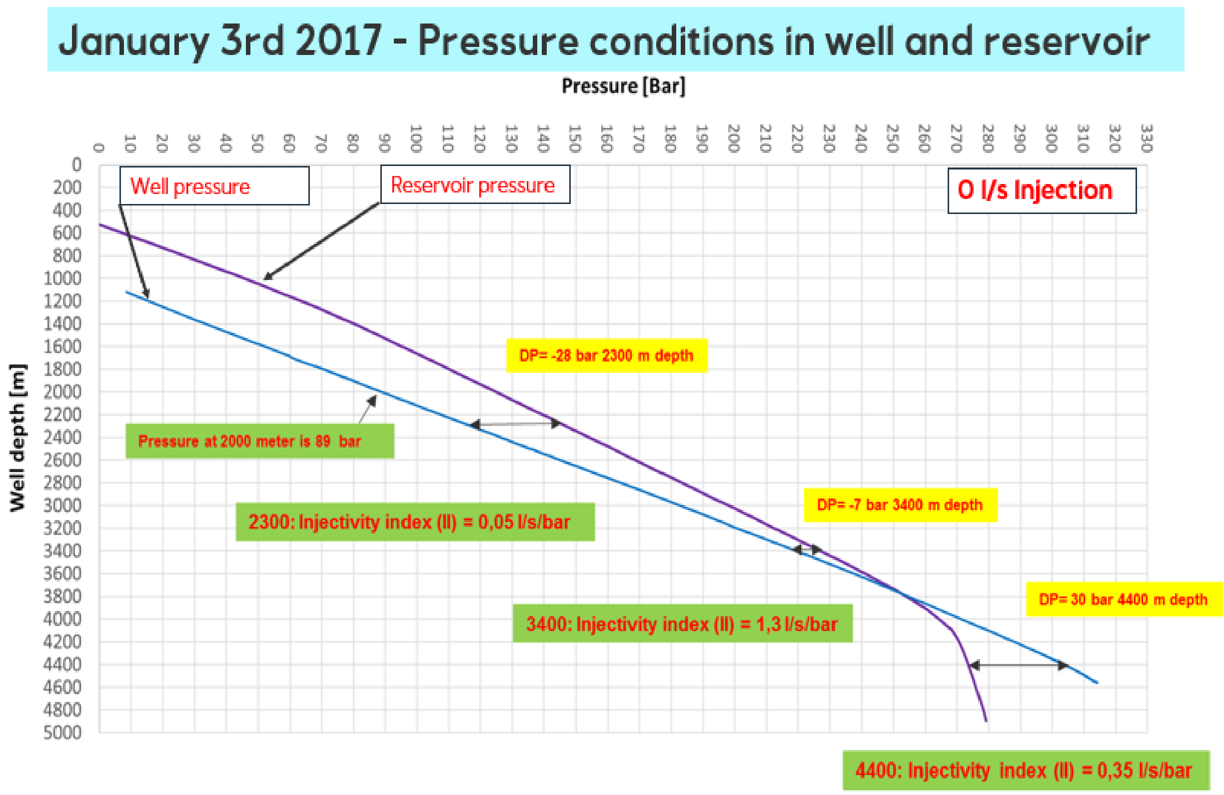

Figure 4: The figure shows reservoir pressure and well pressure for the IDDP-2/DEEPEGS well at ZERO injection rate. Differential pressures are indicated at the three different main production zones at 2300, 3400 and 4400 meters depth.

The situation already described is with zero water injection. In Figure 5 the situation is shown with 45 l/s water injection rate into the well. It can be stated that the pressure inside the well is moved to a higher level while the reservoir pressure is unchanged. At this situation it can be stated that the pressure differences are different and the pressure inside the well has generally increased because the water level in the well will increase with increased water injection rate. It can be stated that the differential pressure at 2300 meters depth is zero and there will be minor exchange of fluid inside the well and the reservoir. At 34000 meters depth the overpressure in the well is 20 bar and at 4400 meters the overpressure of the well is 57 bars. At the two lowermost zones (3400 and 4400 meters depth) fluid will flow from the well into the reservoir.

At 45 l/s injection rate it can be stated that the difference pressure between reservoir and well pressure is almost zero at 2300 meters depth. This corresponds very well with temperature measurements shown in Figure 2. By running the tool down the injection rate were 40 l/s (Weisenberger et al (2017) and it can be stated that there is no step in temperature difference. This can be explained by the difference pressure between the reservoir and well is close to zero in this case corresponding very well with pressure conditions at 2300 meters depth in Figure 5. When pulling the tool out of hole the injection rate was decreased to 15 l/s (Weisenberger et al (2017) and a step in temperature is shown in this location. See Figure 2. This correspond with an expected overpressure in the reservoir at this location at low injection rates, and reservoir fluid is flowing into to the well at the damaged zone at 2300 meters depth. See Figure 4 representing zero injection rate.

It is possible to establish the local II for the IDDP-2/DEEPEGS well by taking the different pressure differences of reservoir and well at the different potential production zones for different injection rates and to keep the injection water rate balance for the total system. The local II for the different depths at 2300 (0,05 l/s bar), 3400 (1,3 l/s bar) and 4400 (0,35 l/s bar) meters depth are then calculated for the January 3rd 2017. The numbers are shown in Figure 4 and Figure 5.

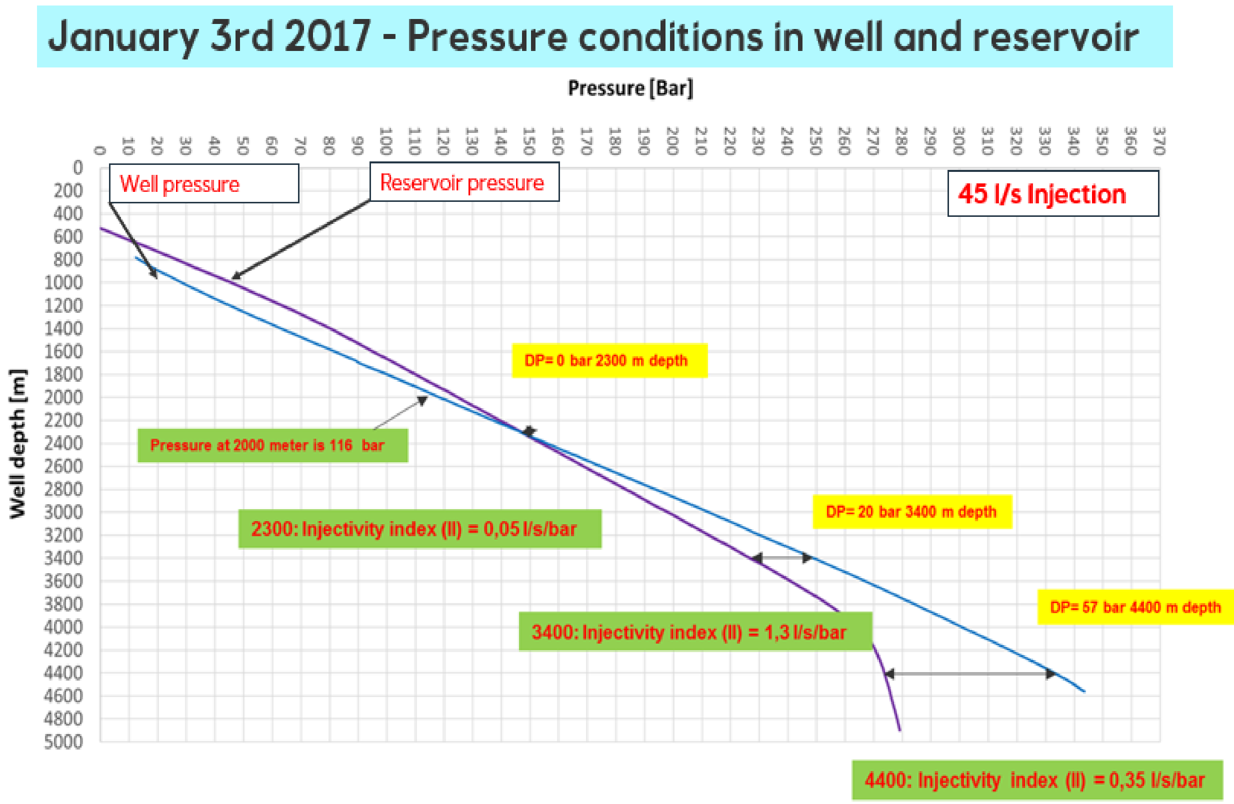

Figure 5: The figure shows reservoir pressure and well pressure for the IDDP-2/DEEPEGS well at 45 l/s injection rate. Differential pressures are indicated at the three different main production zones at 2300, 3400 and 4400 meters depth.

During this work there has been a lot of discussions on the reservoir pressure. Is it possible that there exists a tight rock at the deepest part and/or is it possible with a sort of cap rock in the deeper part of the reservoir? In that respect the pressure in the deepest part of the reservoir should be considerably higher compared to a hydrostatic reservoir pressure. It can be stated that a high reservoir pressure as shown in Figure 6 is not possible with the performed well pressure measurements. In this case the reservoir pressure is always higher than the pressure inside the well with ZERO water injection. This scenario will not be possible with respect to water mass balance within the well where the reservoir pressure is always higher than the pressure inside the well.

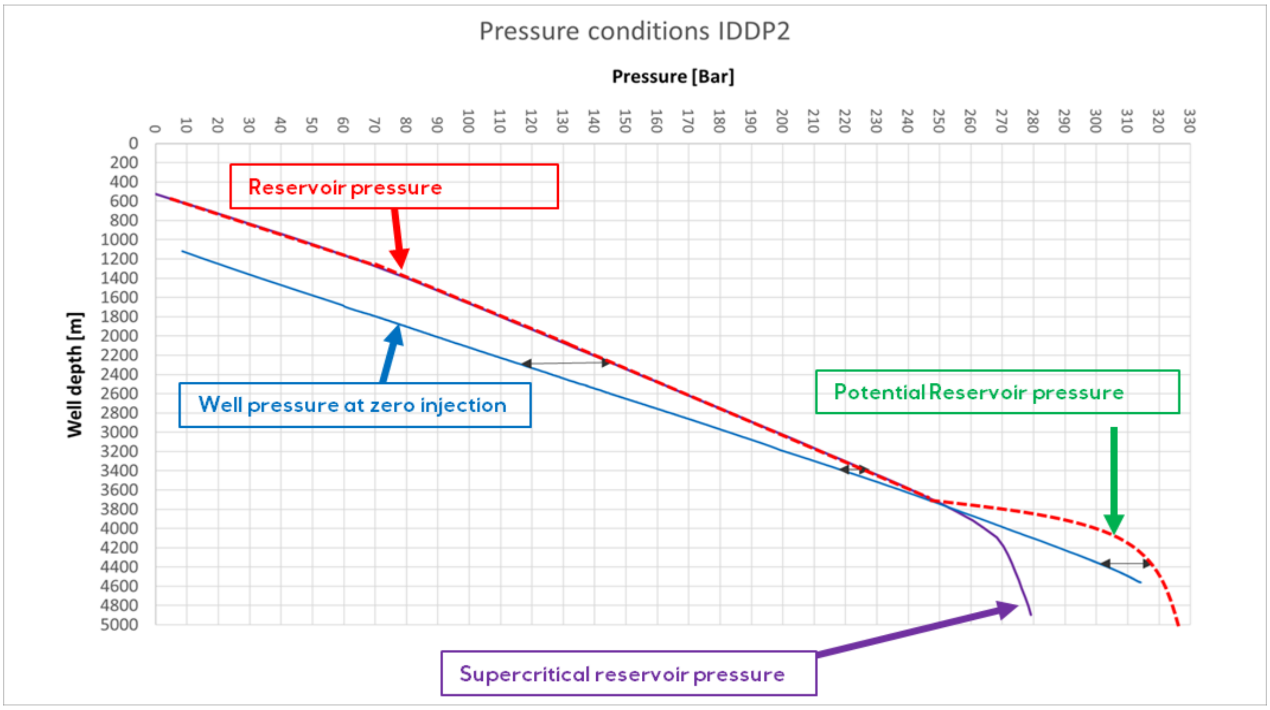

Figure 6: The figure shows a scenario with high reservoir pressure at the lower part indication reservoir pressure above well pressure for the whole well. The pressure profile inside the well is represented by ZERO injection rate. This reservoir pressure scenario cannot be possible with the pressure measurements performed in the well. The water balance in the well cannot be fulfilled in this case.

There is established local II for three different times in the IDDP-2/DEEPEGS project based on overall II measurement. The well has been actively stimulated by injection of cold water into the well between the actual periods. Especially between January 3rd and 23rd 2017 there was an active stimulation period. In this period the total II increased from 1,7 l/s bar to 3,1 l/s bar and mainly the 3400 meters depth zone seems to be stimulated. The results are shown in Figure 7. It can be stated that the zone with the highest local II is located at 3400 meters depth marked with red in the figure. The II at 2300 meters depth location is very low, and it is due to the damage of the casing marked with blue in the figure. The local II of the lowermost part at 4400 meters (yellow in the figure) are lower compared to the main production zone at 3400 meters depth. This overall analysis shows that the IDDP-2/DEEPEGS well will produce mainly from the 3400 meters depth production zone at subcritical reservoir conditions. It will most probably produce a small share from a supercritical part of the reservoir which is represented by the lowermost part at 4400 meters depth. However, this well is rather important to understand supercritical reservoirs and the relatively production rates from the well will be related to the production load of the well. A production rate at very low load will set up a different pressure regime inside the well compared to a max load operation. The relative production rates will then vary from the different production zones. This is one of the main goals to point out in this work, and it will be discussed further.

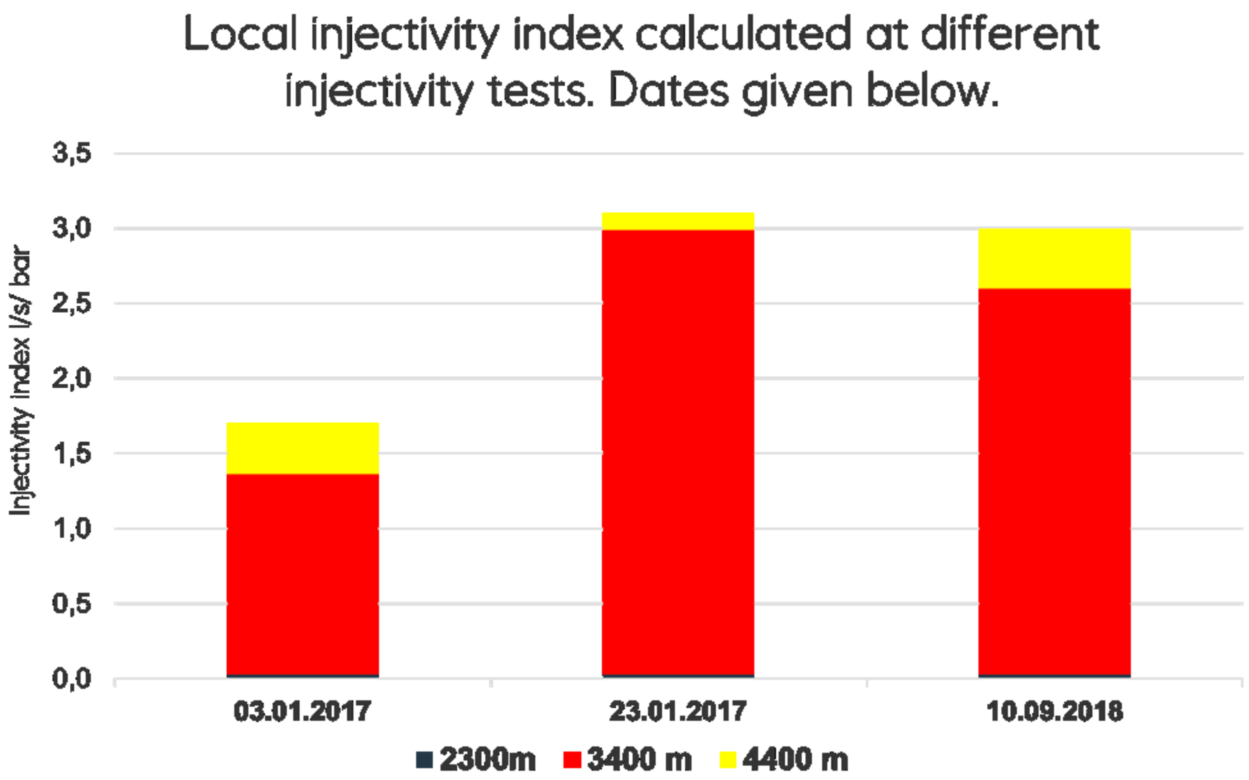

Figure 7: The figure summarizes the local injectivity indexes (II) for the different production zones at 2300, 3400 and 4400 meters depth. Data is shown for three different injectivity test in IDDP-2/DEEPEGS well history.

Figure 7 shows the II found for three different times for injectivity tests at the IDDP-2/DEEPEGS well. The times are January 3rd and January 23 rd 2017 after an active stimulation period of the well. The latest injectivity test is from September 10th 2018. The overall II are almost the same for the two latest tests with 3,1 and 3,0 l/s respectively. In the further analyses the local II found in the calculations will be used to estimate the flow performance of the well. The local II for the different zones in the flow performance calculations are:

- II of 0,05 l/s at 2300 meters depth
- II of 2,7 l/s at 3400 meters depth
- II of 0,3 l/s at 4400 meters depth

These local II are used to estimate the different productions rates for a hot flowing IDDP-2/DEEPEGS well. The local II are used as productivity indexes in the flow calculations. This is not necessarily scientifically perfect, but will indicate a flow potential for the well and at least show the potential for flow from different depths of the IDDP-2/DEEPEGS reservoir. The flow performance of the well is modelled in UniSim (UniSim, 2019). The correct production liner diameters of the IDDP-2/DEEPEGS well at different depths are included in the model.

It is important to point out the potential for production from the different parts of the reservoir to get most possible information of the fluid from the deepest part. This lowermost part of the reservoir is at supercritical conditions and new information from such a reservoir is of highest value in exploring geothermal reservoirs for supercritical conditions.

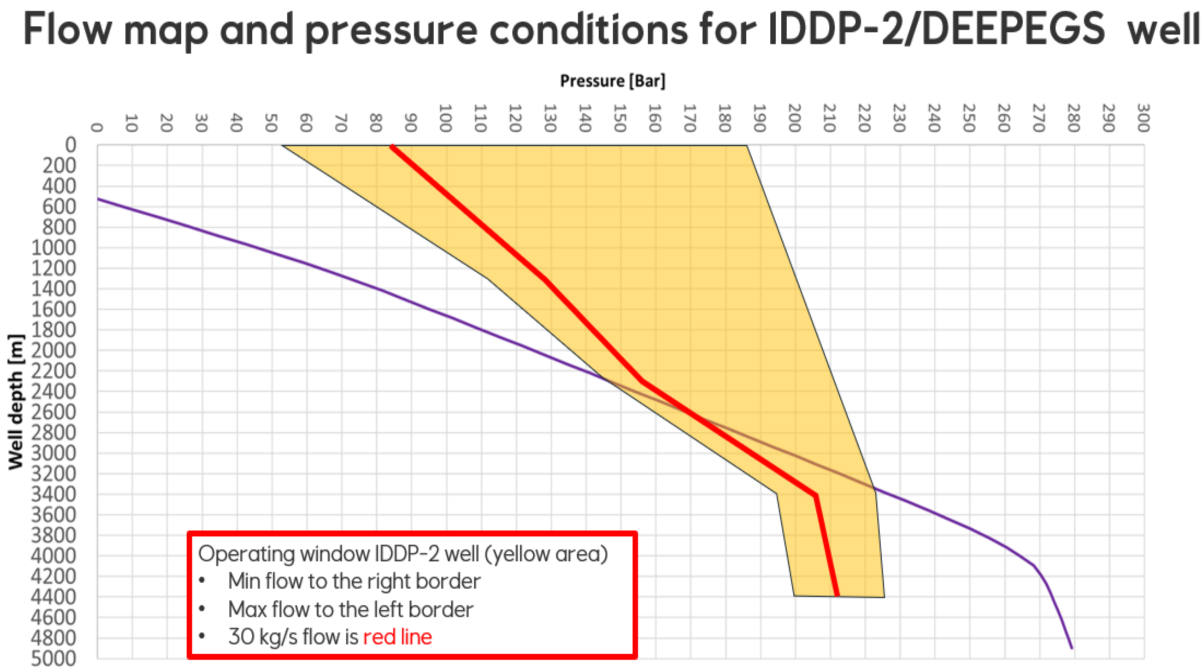

Figure 8: The figure shows the pressure conditions in the IDDP-2/DEEPEGS well during hot production. The red line is representing a production rate of 30 kg/s. The leftmost border represents the pressure in the well during full load and the rightmost close to zero production. Reservoir pressure is also shown as violet line.

The calculations show high relatively production rate from the 3400 meters depth of the well. Approximately 96% of the flow will be from the 3400 meters zone at high flow rates above 30 kg/s. Only 4 % of the flow will have its origin from 4400 meters depths. See Figure 9. One important result is that the influence of the damaged zone at 2300 meters depth will not influence the flow at a certain level because the pressure difference between reservoir and well at this location is small at high flow rates. This is of course when it is only a hole in the casing and not a casing collapse or flow obstruction which will affect the flow and pressure losses in a different way.

At low flow rates the share of the production from the deepest part (4400 meters depth) will increase significantly. At very low flows and close to shut in of the well a production share above 40% should be achievable. The production from each zone is very sensitive for low flow rates. The calculations assume a point production at 3400 meters depth, but the real production will be from a certain length of the well and this will of course affect the production rates. One important result of these calculations is that there should be a certain possibility to investigate fluids from a supercritical reservoir even though the main production zone seems to be at 3400 meters depth and at sub supercritical reservoir conditions. At very low flow rates the pressure in the well is clearly above the reservoir pressure at 2300 meters depth. This means that this zone will not affect the chemistry of the geofluid flowing, but a certain amount of the fluid will be lost into the reservoir at this location at low flow rates. The total loss of fluid is not very high, and it will in reasonable cases be below 10% of the total flow at low flow rates.

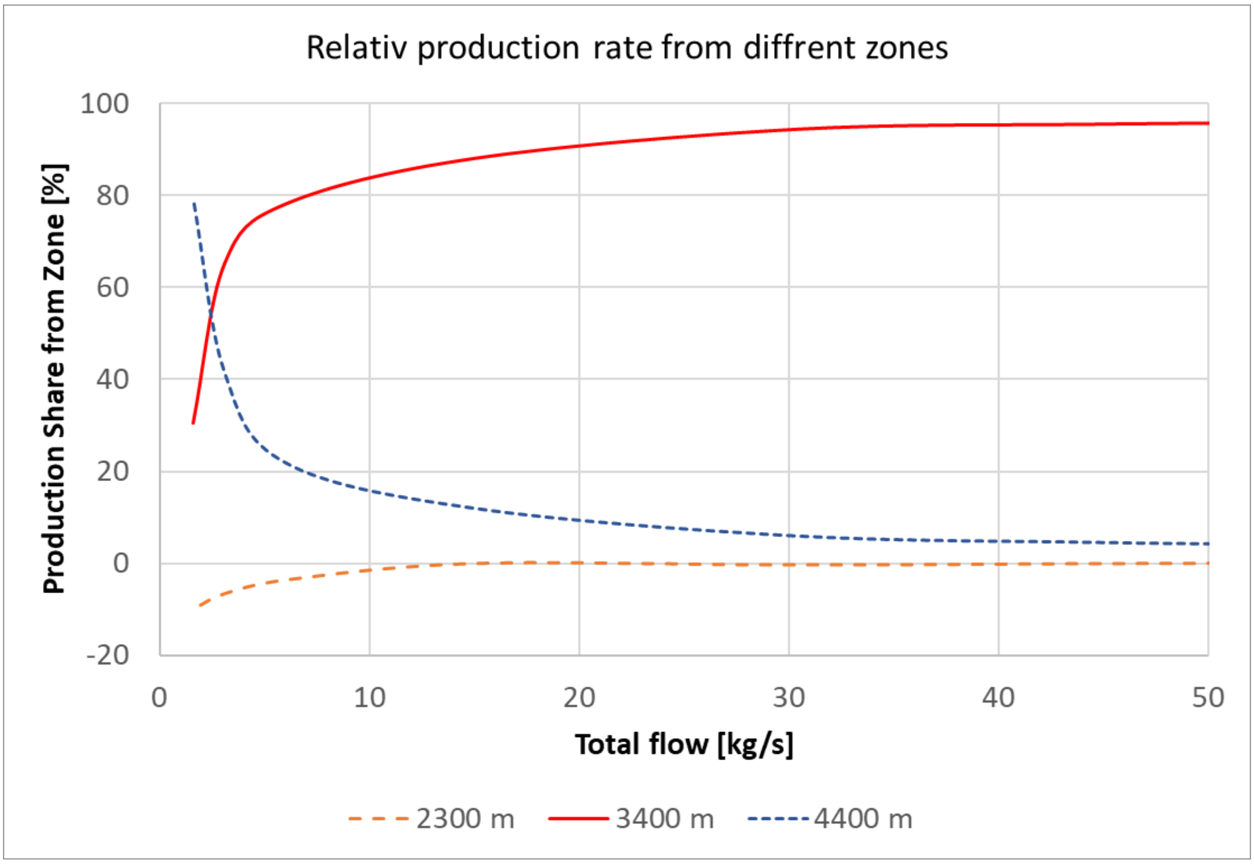

Figure 9: The figure shows the relative production rates from the different zones at different production rates. At low production rates the relatively production from the deepest part at (4400 meters depth) is increasing.

The vapour fraction of the production upstream the control valve at top side will change for the different loads of the well production. This is connected to the fact that the relatively production from the different zones will change because of different pressure conditions in the well at different loads. At high production loads the main production is from 3400 meters depth, and the vapour fraction of the geofluid is around 30 % upstream the control valve. At low production rates the control valve must be nearly closed, and the pressure conditions is the well will increase. See Figure 8. The relative production rate from the lowermost part increase, and the steam quality at top side increase at low flows. At nearly closed well the theoretically steam quality is 100 %.

The steam quality is rather challenging to estimate and the numbers in Figure 10 are uncertain. The estimation of the quality of the steam is based on the reservoirs original pressure and temperature. When the flow in the system is establishing, there will be a certain drawdown in the reservoir in the vicinity of the well. This drawdown will reduce the pressure in this part of the reservoir and lower the saturation point for steam and thereby the saturation temperature. This can set up a situation where the massive amount of rocks in the reservoir will get an overtemperature related to the saturated conditions for the geofluid. This can in turn result in a superheating process of the geofluid flowing into the well. Another scenario is that the well has absorbed huge amount of injected cold water after the well was drilled. This amount of water has cooled down the formation. It may take several months to drain the cold water and get hotter geofluid with its origin temperature to flow into the well. From this point of view the steam quality can be difficult to estimate. The flowing the well will give the answers.

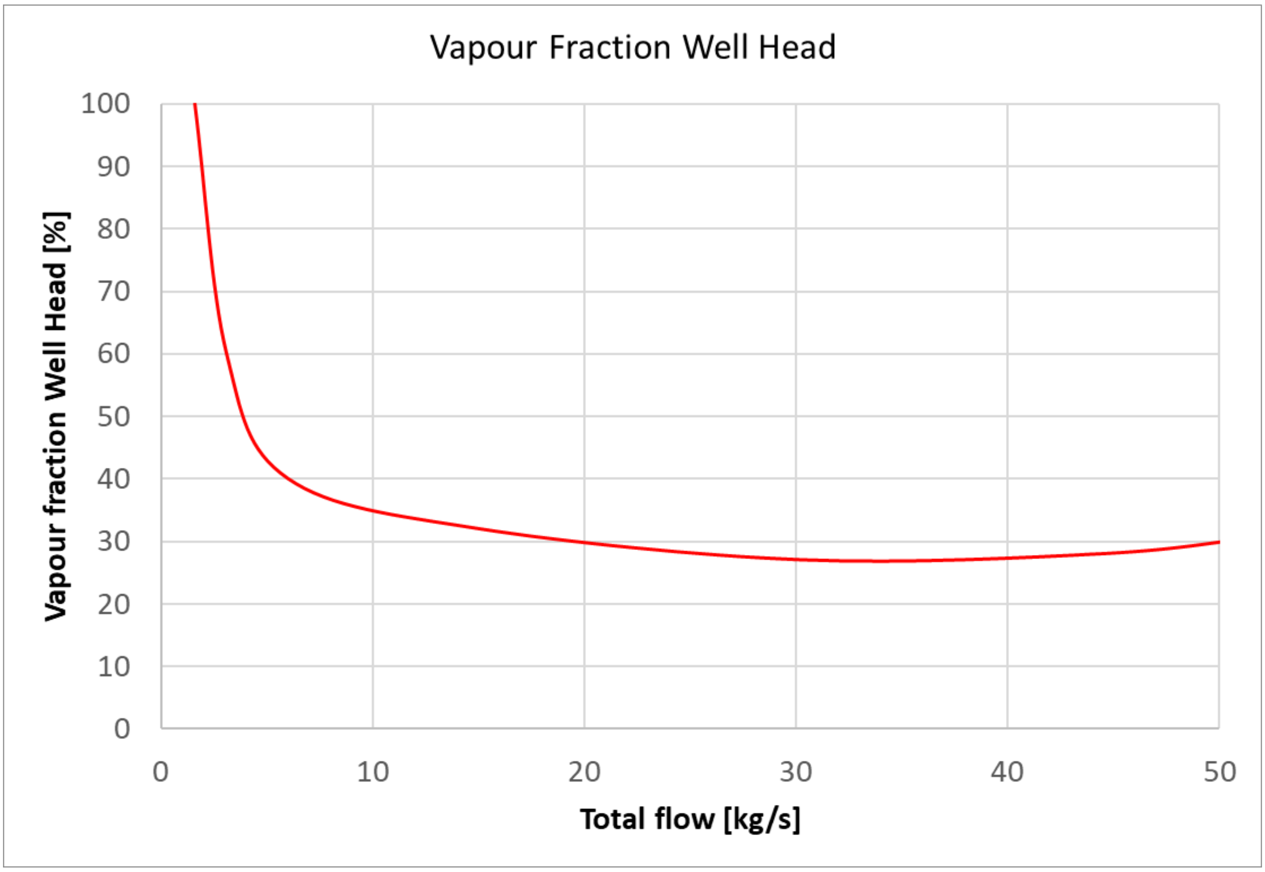

Figure 10: The figure shows theoretically steam quality upstream control valve at top of the well during different loads for the IDDP-2/DEEPEGS well.

4. CONCLUSIONS

The IDDP-2/DEEPEGS well has 4650 meters Measured Depth (MD) and the Total Depth (TD) is 4480 meters. The well was completed in 2017, but is still not started for hot production. This work has used injectivity index (II), temperature and pressure measurements in different stages of the project to point out the major production zones and the ability to produce from the different zones in the well. The major zones in the well is located at 2300, 3400 and 4400 meters measured depth. At 2300 meters depth there is stated that there is a damage of the casing in the well. In this work it is assumed that there is a rift in the casing and connection to the reservoir is established. The hole in the casing is handled as a production zone with respect to the reservoir. Another scenario is that this zone has a casing collapse, and this will influence the flow by a certain flow obstruction. The latter scenario is not discussed in this paper. The far most productive part of the well seems to be at 3400 meters depth. This will be the major production zone when running the well at typical operation loads between 30 - 50 kg/s. Approximately 96% of the production will be from 3400 meters depth and only 4 % from the lowermost part of the reservoir at 4400 meters depth. At high flow rates the damaged zone at 2300 meters will have low influence, and a small amount of the fluid will interchange with the reservoir. The lowermost part of the reservoir is at supercritical conditions, and it is important to flow the well in such a way that most possible understanding from this type of reservoir is achieved. Calculations show relatively lager amount of fluid from the lowermost part of the reservoir at low total flow rates. The pressures inside the well will change during different operation loads, and at low loads up to 40 % of the production can be achieved from the lowest part of the reservoir. Analyses at different loads can therefore estimate the fluid contaminants in the super critical reservoir. At low flows the pressure inside the well is higher and a certain amount of the fluid will be lost in the damaged zone at 2300 meters depth. This will not influence the contamination of the produced fluid and important analyses of the fluid can still be achieved. The vapour fraction of the produced fluid will also change during different flow loads of the well. At high flow rates the steam quality are calculated to approximately 30% and at very low flow rates there can be achieved close to 100% steam quality. These estimates are uncertain because of the high volumes of injected water into the IDDP-2/DEEPEGS well after completing the well and a certain cooling of the reservoir may have happened.

5. ACKNOWLEDGMENTS

I thank my colleagues in Equinor and representatives from HS Orka for valuable input and the availability of data for the investigations performed in this work. Part of this research was supported by the EU H2020 project DEEPEGS Grant Agreement No 690771.

REFERENCES

Friðleifsson, G.Ó., Elders, W.A., Þorhallsson, S., and Albertsson, A.,2005. The Iceland Deep Drilling Project – A Search for Unconventional (Supercritical) Geothermal Resources: Proceedings World Geothermal Congress, Antalya, Turkey

Friðleifsson, G.Ó., Elders, W.A., and Albertsson, A., 2014a. The concept of the Iceland deep drilling project: Geothermics, 49, 2-8.

Friðleifsson, G.Ó., and Elders, W.A., 2017. Successful Drilling for Supercritical Geothermal Resources at Reykjanes in SW Iceland: GRC Transactions, 41, submitted.

Friðleifsson, G.Ó., Sigurdsson, Ó., Þorbjörnsson, D., Karlsdóttir, R., Gíslason, Þ., Albertsson, A., and Elders, W.A., 2014b. Preparation for drilling well IDDP-2 at Reykjanes: Geothermics, 49, 119-126.

Fridriksson, T., Stefánsson, A., Óskarsson, F., Eyjólfsdóttir, E., Sigurdsson, O., 2015. Fluid Chemistry Scenarios Anticipated for IDDP-2 to be Drilled in Reykjanes, Iceland. Proceedings World Geothermal Congress 2015, Melbourne, Australia.

Hokstad, Ketil and Tänavsuu-Milkeviciene, Kati, 2017. Temperature Prediction by Multigeophysical Inversion: Application to the IDDP-2 Well at Reykjanes, Iceland: GRC Transactions, Vol. 41.

UniSim – Software for Process Design and Simulation, Honeywell, Equinor licence, 2019

Weisenberger, T., Harðarson, B., Kästner, F., Gunnarsdóttir, S., Tulinius, H., Guðmundsdóttir, V., Einarsson, G., Pétursson, F., Vilhjálmsson,S., Stefánsson, H., Níelsson, S. DEEPEGS: DEPLOYMENT OF DEEP ENHANCED GEOTHERMAL SYSTEMS FOR SUSTAINABLE ENERGY BUSINESS. Deliverable: D6.4: Drilling Report 3 – Final Report on Drilling. Well Report – RN-15/DEEPEGS/IDDP-2. Drilling in Reykjanes Phases 4 and 5 from 3000 to 4659 m, 2017.