

The Iceland Deep Drilling Project (IDDP): Reaching into the Roots of Iceland's Volcanic Geothermal Fields

Gunnar Gunnarsson¹, Thráinn Fridriksson¹, Pálmar Sigurðsson¹, Ingvi Gunnarsson¹
Bjarni Reykr Kristjánsson¹, Vala Hjörleifsdóttir¹, Sandra Ósk Snæbjörnsdóttir², Kolbrún
Ragna Ragnarsdóttir³

¹ OR – Reykjavík Energy

² Carbfix

³ ON Power

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ABSTRACT

The Iceland Deep Drilling Project (IDDP) was launched in the early 2000's. The project is a consortium of the largest power companies in Iceland; OR-Reykjavik Energy, Landsvirkjun, and HS-Orka also including other domestic and international partners. The plan was that each company would drill a deep superhot well in their own geothermal field. Well NJ-11 in the Nesjavellir Geothermal field was unexpectedly drilled into a very hot formation (>380°C) in 1985. The well design and build were inadequate to handle the pressure and the lowest part of the well had to be sealed off. However, this incident gave birth to the idea of solving the technical challenges of drilling into the roots of volcanic geothermal systems in Iceland to produce superhot or supercritical fluid.

The first well of the project, IDDP-1, was drilled in the Krafla geothermal field, N-Iceland, into magma at the depth of 2.1 km, making it impossible to reach the planned 4.5 km depth. However, it was possible to do flow tests in the well and it yielded superhot steam. The chemistry of the fluid was challenging, and the casing failed because of the extremely high stresses due to thermal expansion and contraction. The second well, IDDP-2, was drilled down to 4.6 km in Reykjanes, SW-Iceland. The highest measured temperature and pressure in the bottom of the well were 426°C and 340 bar respectively. However, during recovery the casing of the well failed and since then it has been impossible to reach the bottom part of the well.

The next IDDP well, IDDP-3, will be drilled in the Hengill Area SW-Iceland. It's likely that the formation which NJ-11 was drilled into will be chosen as a target for IDDP-3. The experience from wells IDDP-1 and IDDP-2 have shown that the conventional geothermal well design is likely to fail in superhot wells. For the project to succeed, major technical challenges must be solved. These challenges include extreme casing stresses due to thermal expansion/contraction, high-temperature and pressure effect on the casing cement and the corrosive environment. Addressing those issues will take an interdisciplinary approach. A novel well design must be developed to ensure well integrity during production for the project to be a success.

If successful it will open a new frontier in geothermal power production. Abundant resources below current geothermal reservoirs could become accessible to increased production of clean energy.

1. Introduction

Conventional geothermal steam production wells normally reach to the depth of 2-3 km (Sveinbjörnsson (2014)). The heat sources are normally below the depth range of conventional production wells. Thus, the conditions in deeper layers are not well known but one can expect that vast geothermal resources are located below explored geothermal reservoirs. Tapping into those resources by expanding the production downwards, will prolong the lifespan of geothermal developments and/or increase the output of the geothermal field. There are, however, numerous challenges in utilizing the deeper geothermal systems, such as high stresses in casings due to high temperature differences and corrosive geothermal fluids (see e.g., Kaldal et al. (2016b) and Ármannsson et al. (2014)). In order to utilize those deeper resources in an economically sound way, it is necessary to find cost effective solutions to those challenges.

There are few projects focusing on production from superhot geothermal resources, such as *Japan Beyond Brittle* and the *New Zealand Geothermal the Next generation* project. The Iceland Deep Drilling Project (IDDP) was launched in the early 2000's. The biggest power companies in Iceland; OR, Landsvirkjun, and HS-Orka formed a consortium with domestic and international partners. The plan was that each company would drill a deep well in its field, with the objective to characterize the physical and chemical conditions in the roots of high temperature geothermal systems and find an economically sound method of harnessing the energy stored there.

The definition of high temperature geothermal systems in Iceland is that the temperature at the depth of 1 km is higher than 150°C. Such systems are found in and around the volcanic active rift zones. Fig.1 shows a schematic model of such a geothermal system. Seven geothermal power plants that use high-temperature resources are operated in Iceland. The typical depth of a well in such a field is around 2500 m and the temperature measured in the wells follows boiling point curve in the hottest parts of the fields and can reach over 330°C.

The heat sources of the geothermal systems are believed to be magmatic intrusions. The depth of the heat sources is normally believed to be below the depth ranges of the wells that occasionally reach the depth of more than 3 km but are normally around 2500 m deep (as mentioned above). The exact depth and nature of the heat sources is not fully known. Neither is the depth range of the water circulation. It is also an objective of the IDDP project to obtain information to answer fundamental questions on properties of the deeper reservoirs, not only by

drilling, but also by using state of the art exploration methods to localize feasible targets for deep drilling.

The first well of the project (IDDP-1) was drilled by Landsvirkjun in Krafla, NE-Iceland. The planned depth was ~4.5 km, but it was unexpectedly drilled into magma at the depth of 2.1 km. Even though the open part of the well was very short (casing reaching down to 1950 m and final depth of the well was 2077 m) it was possible to flow test the well. The well was indeed powerful. The maximum well head temperature was 450°C and well head pressure was 40–140 bar during flow tests. It was estimated that the well could produce up to 36 MW_e. However, it was difficult to handle the fluid chemistry (corrosion and silica scaling) and the casing failed due to extreme thermally induced stresses (Kaldal et al. (2016a), Karlsdottir et al. (2015)). Thus, the well had to be shut down permanently (Friðleifsson et al. (2015)).

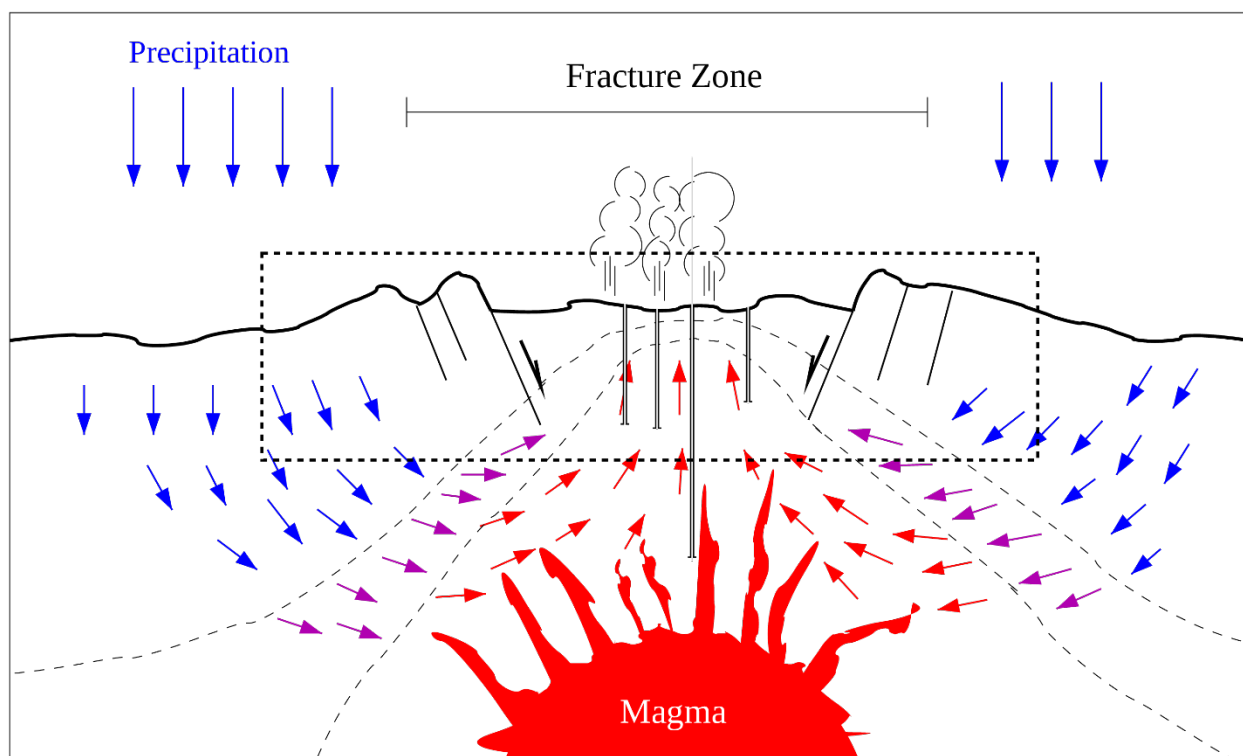


Figure 1: A schematic illustration of a geothermal system in the Icelandic rift zone. The heat sources are magmatic intrusions. Permeability is fracture dominated and the rifting creates and maintains permeability. Only the uppermost part of the system is known through direct measurements. The goal of the IDDP project is to drill into the roots of the system in order to explore and, if possible, harness the resources there.

The second well of the project was drilled by HS-Orka in Reykjanes, SW-Iceland. It reached planned depth of 4600 m. The highest temperature and pressure measured in the well were 426°C and 340 bar respectively. The formation temperature in the bottom of the well has been estimated to be around 500°C using multigeophysical inversion methods and up to 600°C using petrological and geochemical methods (Hokstad and Tånavsuu-Milkeviciene (2017); Friðleifsson et al. (2021)). However, due to casing failure, only the uppermost 3000 m are currently accessible.

Now the third well in the project, IDDP-3, is being planned in the Hengill Area, SW-Iceland. There are a few interesting targets in the area, the most promising one is in Nesjavellir in the center of the field where well NJ-11 was drilled into very hot formation ($>380^{\circ}\text{C}$) in 1985 at the depth of 2100 m. It is obvious that the main challenge in drilling a superhot well is the well integrity. Before drilling IDDP-3 those challenges must be solved.

2. Interesting targets in the Hengill Area

The Hengill area (see map in Fig.2) is located ~ 25 km SE of Reykjavík. Due to its proximity to Reykjavík and surrounding communities the geothermal field in the area are an important energy source for space heating and electricity. Currently there are two co-generation power plants operated in the area: Nesjavellir in the north with installed capacity of 120 MWe in electricity and 300 MWth in thermal energy and Hellisheiði in the south with installed capacity of 303 MWe in electricity and 200 MWth in thermal energy.

The Hengill volcanic system consists of Mt. Hengill and SSW-NNE oriented fissure swarm intersecting it. The surface rocks in the area are mainly basaltic in form of hyaloclastites from glaciation periods and lavas from interglacial periods. Three Holocene eruptions are known in the Hengill system 2000, 5800, and 10,000 years ago and hot springs and fossil geothermal activity can be found all over the area (Sæmundsson (1967), (1995)).

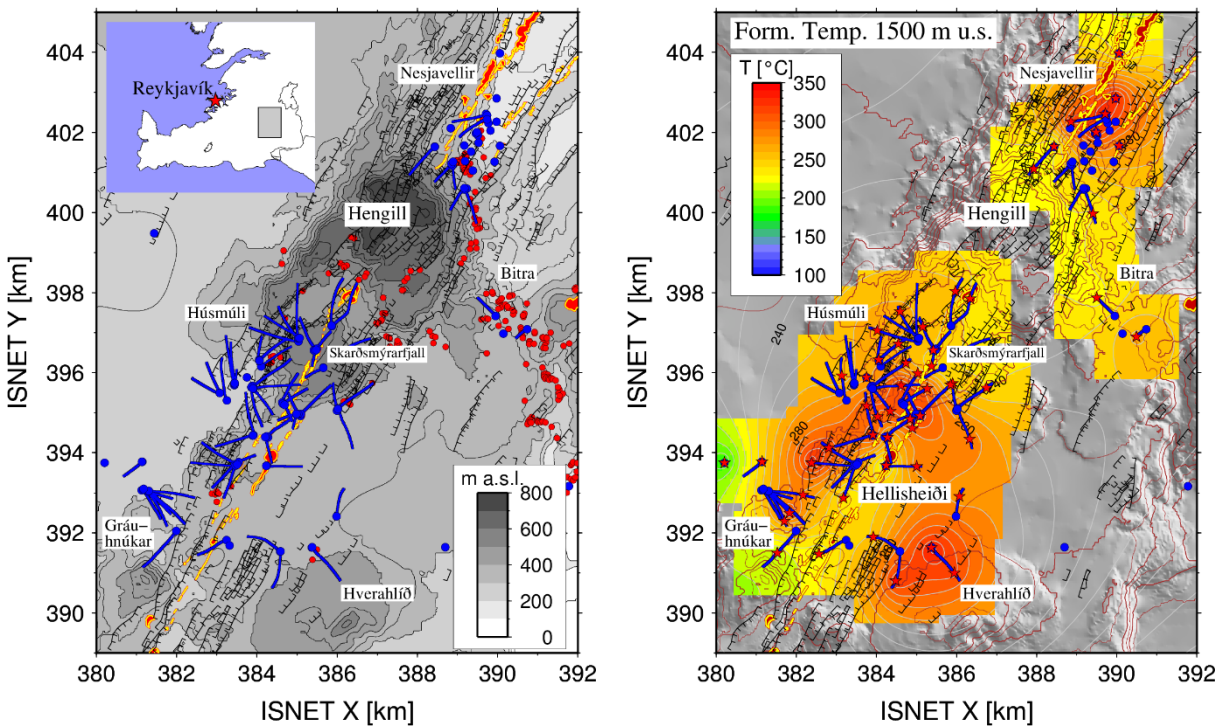


Figure 2: The Hengill Area. To the left: A topographic map showing well head and well paths of directionally drilled wells (blue dots and lines respectively), hot springs and fumaroles (red dots) and Holocene eruptive fissures (red and yellow areas). The inset shows the location of the Area in SW Iceland. To the Left: Formation temperature at the depth of 1500 m below sea level. The red stars show the data points (i.e., the intersection of the wells and 1500 m b.s.l.).

The formation temperature in the area is also shown in Fig 2. The highest temperatures are found in relatively narrow areas. These maxima are found in Nesjavellir in the north and west of the eruptive fissure in Hellisheiði in the south and in Hverahlíð on the southern edge of the area. In these areas the temperature is at boiling-point curve. In between these hot zones are cooler areas. The biggest portion of the production from the geothermal fields comes from the hottest areas (Gunnarsson and Mortensen (2016), Gunnarsson et al. (2011)).

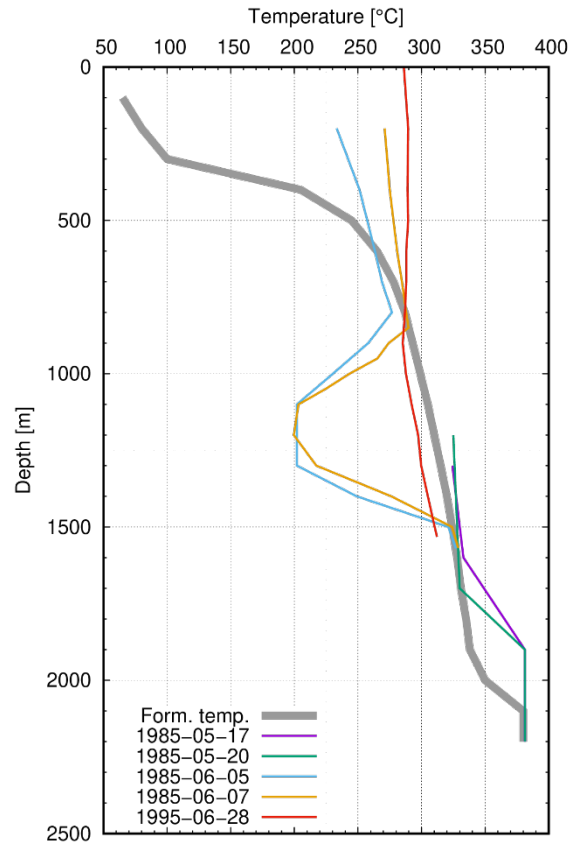


Figure 3: Few temperature measurements from well NJ-11 shown with estimated formation temperature (Form. Temp.). The first two measurements (1985-05-17 and 1985-05-20) reached the deepest part of the well. Those measurements showed temperature of 380°C (which was the upper limit of the measuring instrument). Measurements 1985-06-05 and 1985-06-07 were done during recovery after sealing off the bottom part and 1995-06-28 during flow tests.

2.1 Nesjavellir

The most promising target for a superhot well is assumed to be in Nesjavellir. In 1985 well NJ-11 there was drilled into a very hot formation ($> 380^{\circ}\text{C}$) at the depth of ~ 2000 m. Well NJ-11 had a relatively short production casing or 565m and feed zone just below the casing. When the well had been drilled into down to 2200 m an underground blowout from deep feed zones up to feed zones just below the production casing made it almost impossible to control the well. In order to gain control of the well, the lowest part of it was sealed off with gravel resulting in a

final depth of 1600 m. However, two temperature measurements exist from the lower parts of the well done while the drilling string was still in the wells (see Fig.3). Those measurements showed temperature $>380^{\circ}\text{C}$ (380°C was the upper limit of the measurement range of the instrument used). There are no pressure measurements available from the lower parts of the well. The pressure in the bottom was estimated to have been >220 bar using the weight of the water column in the well and the well head pressure while injecting into the well. Thus, the well was believed to have reached supercritical conditions (Steingrímsson et al (1990)). This is however uncertain. Big portions of the well might have been in two phase state, due to flow from lower feed zones up to shallower ones.

After NJ-11 was drilled it was like a commandment that one should not drill deeper than 2000 m in the hottest part of the Nesjavellir field. Nevertheless, this incident sparked the idea of drilling into the hot formation near NJ-11 Nesjavellir and being prepared for the conditions there. Thus, NJ-11 in a way spawned the idea of the Iceland Deep Drilling Project (IDDP). The abovementioned commandment of not drilling deeper than 2000 m in Nesjavellir was honored until recently.

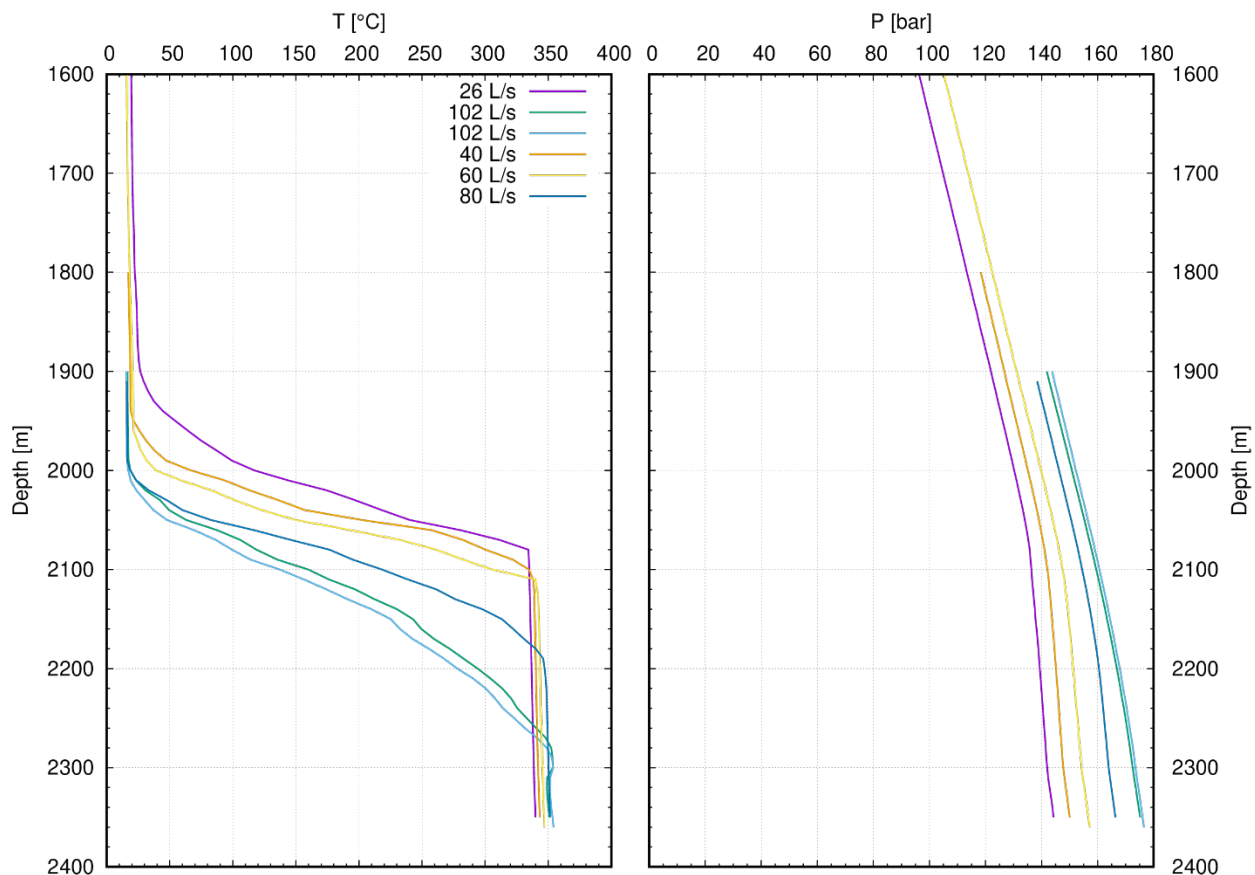


Figure 4: Temperature (T) and pressure measurements (P) in well NJ-32 in Nesjavellir. The measurements were run in the same day at different rates of injection (Q). At the depth of ~ 2300 m the pressure and temperature are always at boiling point curve for different rates of injection – suggesting that the system is superheated.

The most recent production well that was drilled in Nesjavellir (NJ-32) was planned to be drilled into the close vicinity of the hot formation encountered by well NJ-11. The well design of NJ-32 was conventional. It was however better equipped than well NJ-11 to be able to handle high temperatures and pressures. The production casing was 1100 m long and the drilling rig and well head had higher temperature and pressure rating than of NJ-11. The well NJ-32 was drilled down to 2400 m MD (2150 m TVD), and it showed very interesting behaviour. In Fig.4 temperature and pressure logs from injection tests during well completion program are shown. It is evident the well has been drilled into superheated formation at the depth of ~2300 m. The colder water reaches deeper as the injection rate is increased. However, even at the injection rate of 102 L/s the water did not reach the deepest ~100 m of the well. What is interesting is that around the depth of 2300 m the temperature matches the boiling point temperature at the pressure in the well at that depth as it changes with varying injection rate.

The results from measurements in that well are described further in Fridriksson et al. (2022). The main results from the well are that the superhot conditions encountered by well NJ-11 are still there – even though the field has been under production since 1991. Another result – described in more detail by Fridriksson et al. – is that there were clear signs of corrosive environment in the deepest part of the well, something that has been reported in superhot wells such as IDDP-1. In short, NJ-32 confirms that the hottest part of the Nesjavellir field is an interesting target for a superhot well.

2.2 Hverahlíð

Hverahlíð, in the southern edge of the Hengill system, is also a promising target for a deep well. The highest temperature measured in the southern part of the Hengill system (337°C) was measured in the deepest part of the first well that was drilled in Hverahlíð; HE-21. Fig.5 shows temperature logs from well HE-21. The measurements shown were all done shortly after the well had been flowing. Such measurements show a jump in temperature near the bottom of the well that is not present in other measurements. This indicates that the bottom of the well is drilled close to very hot formation. Another well recently drilled in the vicinity of HE-21 (HE-66) is also very hot in the bottom though not as hot as HE-21.

What also makes the Hverahlíð sector of the Hengill Area interesting is that most of the wells drilled there are very hot (>300°C) and very permeable. The most powerful wells in the Hengill area and in all of Iceland are located there. This high temperature and high flowrate might indicate that the wells are drilled in the vicinity of a shallow heat source.

3. Technological challenges

As mentioned above both wells that have already been drilled in the IDDP project have had casing failures. Casing failures are a known problem in high temperature wells in Iceland (Lohne et al. (2017)). The well design used in geothermal is adapted from oil and gas. There are, however, challenges that are unique to geothermal wells that have not been addressed properly. The main challenge are high stresses due to thermal expansion/contraction. A typical production casing in a high temperature well in Iceland is ~800 m long. The temperature when it is cemented is well below 100°C. The well can reach temperatures ~300°C during recovery and if the well must be shut-in the temperature can drop again to less than 100°C in portions of the production casing. These large temperature changes cause extreme thermal stresses that can

cause the steel of the casing to deform and even fail – especially during cyclic load (i.e., repeated heating and cooling of the casing).

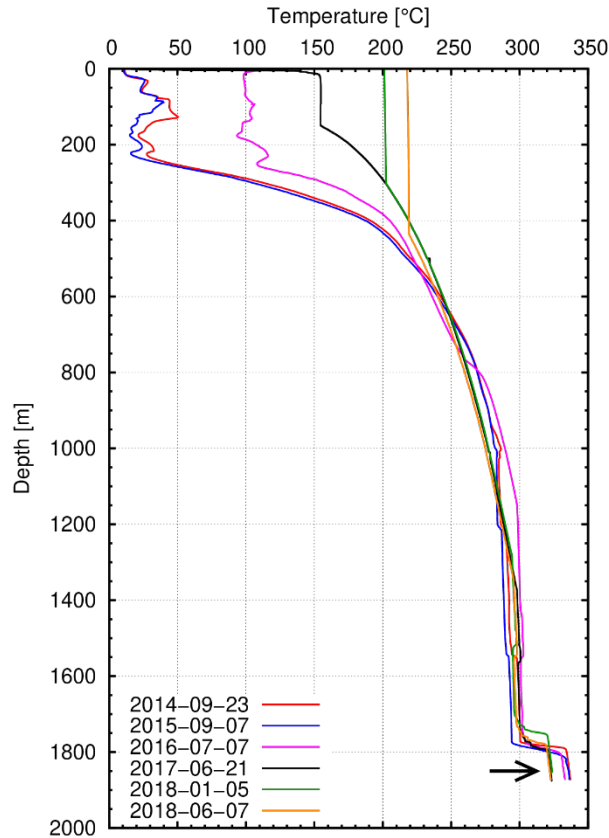


Figure 5: Few temperature logs from well HE-21 in Hverahlíð near the Southern edge of the Hengill systems. All the measurements shown are done shortly after the well had been flowing for longer periods of time. The arrow points to the temperature step visible after long periods of flowing.

In a deep well the casing will be much longer than in conventional geothermal production wells. The idea is to isolate the conventional system from the well and only produce fluid from the deeper formations. Therefore, the length of the production casing will have to be 2000 m or more. The temperatures expected in a deep well can be 500–600°C. Thus, longer production casing and higher temperature differences will cause even higher stresses due to thermal expansion/contraction in deep wells than in conventional wells.

A solution to this problem has been proposed, so-called flexible couplings for connecting the casing pipes, that can take up the expansion of the casing pipes when the well heats up. Experiments with the flexible coupling have shown some promising results and this might be solution for stress mitigation in long casings (Kaldal et al. (2021), Kaldal and Thorbjornsson, 2016). Finding suitable cementing materials and methods is also an important task. The cementing must support the flexible coupling and the cemented casing pipes must be able to slide. Moreover, the cement must withstand the temperatures expected in the well.

Another important issue is the casing material. One can expect corrosive environments in deep geothermal wells. This has been documented in IDDP-1 in Krafla and in well NJ-32 in Nesjavellir as mentioned above. Thus, finding a suitable corrosion resistant casing material is an important task. Corrosion resistant materials are available, but very costly. If deep heat mining is supposed to be economically feasible the solutions must be cost effective. Coating cheaper standard casing material with corrosion resistant more expensive material is among solutions that are being investigated.

4. Producing heat from the depths

The method of mining heat from the depth is dependent on available technology and the conditions in the hot formation. In Fig. 6 three scenarios of mining heat from the roots of the geothermal system are shown.

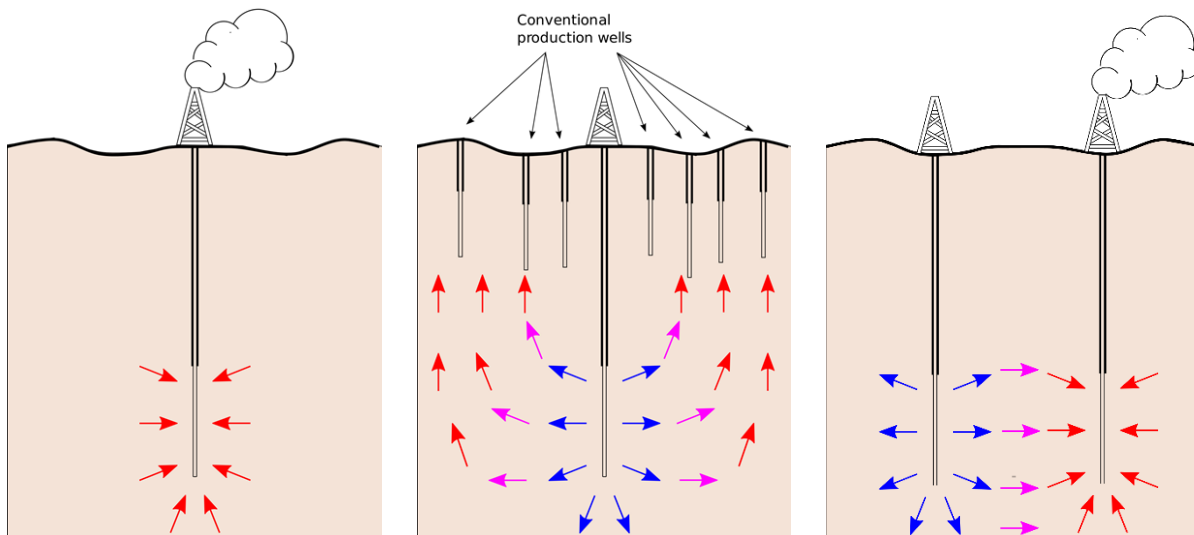


Figure 6: Different scenarios of mining heat from the roots of geothermal system. Left: Direct production of the fluid in the formation. Center: Injecting into the deeper formation providing pressure support for the conventional system above. Right: A well doublet with one well for injection and another for production.

The first one shows the original idea of producing fluid from the deep layers. The conventional system above is cased off by long production casing and only the deep formation fluid enters the well. To realize this scenario, it is necessary to have novel casing and cementing technologies. One can expect extreme stresses induced by thermal expansion/contraction and corrosive fluid. The formation would also have to be permeable enough for the fluid to flow through it and towards the well to maintain flow rates. As one can expect such a well to be quite expensive, the flow rate would have to be significantly higher than from a conventional well in order to have an economically sound production scheme.

The second production scenario shown in Fig. 6 could probably be realized with conventional methods. In that case the well would solely be used for injection. It would never recover in temperature and in would never flow. The injected water is supposed to create permeability by cooling the formation and thus, opening fractures. The water would migrate upwards carrying

the heat from the deep hot formation providing pressure support for the conventional geothermal production above. The rock formation between the injection and production would interact with the fluid, solving potential chemistry problems encountered in superhot wells.

The third production scenario is maybe more farfetched than the other two. That represents a high temperature engineered geothermal system with a well doublet: One well for injection and the other for the production. This might be the method of choice if the superhot formation would have very low permeability and the appropriate technology for ensuring well integrity and dealing with the corrosive environment were available.

5. Conclusion

The next step in developing geothermal technology is to go deeper and produce the resources below conventional geothermal systems. By expanding geothermal production downwards, it will be possible to increase the power output of the geothermal field and/or prolong the lifetime of an existing geothermal development. There are, however, major technical challenges that must be solved before deep heat mining is technologically and economically feasible. Moreover, the conditions in the deeper parts of the geothermal system are not well known. So is the depth range of the water circulation and the nature of the heat transfer between the magma/intrusions and the water.

The aim of the Iceland Deep Drilling Project (IDDP) is to gain knowledge of the roots and heat sources of the high temperature volcanic geothermal systems in Iceland and elsewhere and discover methods of utilizing the deep geothermal resources in an economically and environmentally sound manner.

REFERENCES

- Ármannsson, H, Fridriksson, Th, Gudfinnsson G.H., Ólafsson, M., Óskarsson, F., Thorbjörnsson, D., “IDDP – The chemistry of the IDDP-01 well fluids in relation to the geochemistry of the Krafla geothermal system”, *Geothermics*, 49, (2014), 66–75
- Friðleifsson, G.Ó., Pálsson B., Stefánsson, B., Albertsson, A., Gíslason, Þ., Gunnlaugsson, E., Thorsteinsson, H.H., Ketilsson, J., Sæther, S., Sörlie, C., Elders, W.A., Zierenberg, R.A., “The IDDP success story – Highlights”, *Proceedings World Geothermal Congress 2020+1*, Reykjavik, Iceland (2021)
- Friðleifsson, G.Ó., Pálsson, B., Albertsson, A.L., Stefánsson, B., Gunnlaugsson, E., Ketilsson, J., and Gíslason, Þ., “IDDP-1 Drilled into Magma – World’s First Magma-EGS System Created”, *Proceedings World Geothermal Congress 2015*, Melbourne, Australia (2015)
- Fridriksson, Th., Gunnarsson, G., Sigurdsson, P., Kristjánsson, B.R., Gunnarsson, I., Snaebjörnsdóttir, S.Ó., “Indications of a superhot, HCl bearing steam at Nesjavellir, SW Iceland: Observations from well NJ-32”, *Geothermal Resource Council Transactions*, 46, (2022).
- Gunnarsson, G., Arnaldsson, A., and Oddsdóttir, A.L., “Model Simulations of the Hengill Area, Southwestern Iceland”, *Transp Porous Med*, 90, (2011), 3–22

- Gunnarsson, G. and Mortensen, A.K., “Dealing with intense production density: Challenges in understanding and operating the Hellisheiði Geothermal Field, SW-Iceland”, *PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, (2016), SGP-TR-20
- Hokstad, K. and Tănăvsuu-Milkevičienė, K., “Temperature Prediction by Multigeophysical Inversion: Application to the IDDP-2 Well at Reykjanes, Iceland”, *GRC Transactions, Vol. 41*, (2017)
- Kaldal, G.S., Thorbjörnsson, I., Guðmundsson, L., Reinsch, T., Lipus, M., Wollenweber, J., Orlic, B., Gíslason, Þ., Stefánsson, A., Pálsson, B., Sverrisson, Ó., “Thermal Stress Mitigation Testing of Externally Cemented Flexible Coupling in Geothermal Steam”, *Proceedings World Geothermal Congress 2020+1*, Reykjavik, Iceland (2021).
- Kaldal, G.S., Jonsson, M.Þ., Pálsson, H., Karlsdóttir, S.N., “Structural modeling of the casings in the IDDP-1 well: Load history analysis”, *Geothermics*, 62, (2016a), 1–11.
- Kaldal, G.S., and Thorbjörnsson, I.O., “Thermal expansion of casings in geothermal wells and possible mitigation of resultant axial strain”. *European Geothermal Congress*, Strassbourg France (2016b).
- Karlsdóttir, S.N., Ragnarsdóttir, K.R., Thorbjörnsson, I.O., Einarsson, A., “Corrosion testing in superheated geothermal steam in Iceland,” *Geothermics*, 53, (2015), 281-290.
- Lohne, H.P., Ford, E.P., Majoumerd, M.M., Randeberg, E., Aldaz, S., Reinsch, T., Wildenborg, T., and Brunner, L.G., “Barrier definitions and risk assessment tools for geothermal wells,” *GeoWell*, Stavanger (2017).
- Steingrímsson, B., Guðmundsson, A., Franzon, H. and Gunnlaugsson, E., “Evidence of a Supercritical Fluid at Depth in the Nesjavellir Field”, *PROCEEDINGS, 15th Workshop on Geothermal Reservoir Engineering*. Stanford University, Stanford, California (1990).
- Sveinbjörnsson, B.M., “Success of High Temperature Geothermal Wells in Iceland”, Report ÍSOR-2014/053, ÍSOR (2014).
- Sæmundsson, K., “Hengill, geological map (bedrock) 1:50.000”, *Orkustofnun, Hitaveita Reykjavíkur, and Landmælingar Íslands*, (1995)
- Sæmundsson, K.: Geology of the Thingvallavatn area. *OIKOS*, 64 (1992), 40-68.
- Sæmundsson, K., “Vulkanismus und Tektonik des Hengill-Gebietes in Südwest-Island”, PhD Thesis, Universität zu Köln (1967).