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IDDP-1 Drilled Into Magma – World's First Magma-EGS System Created

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ABSTRACT

The Iceland Deep Drilling Project (IDDP) is a research and development project that is investigating the possibility of greatly increasing the power output of geothermal wells by producing high-enthalpy supercritical geothermal fluid from 4-5 km depths. The aim is to increase the power output per well by an order of magnitude. IDDP is a collaboration project of three energy companies - HS Orka hf (HS), Landsvirkjun (LV) and Reykjavik Energy (OR), and Orkustofnun (OS) (the National Energy Authority of Iceland) that was established in 2000 to investigate the feasibility of utilizing geothermal fluid at substantially higher temperatures and from deeper wells than currently used today. From the onset of the IDDP, international collaboration has been one of the trade mark of the project. Scientists from at least 15 countries have contributed to the science program in various ways by participating in workshops and by publishing articles in international journals. Since 2005 ICDP (International Scientific Drilling Program) and NSF (National Science Foundation of USA) have supported the IDDP program. The international companies Alcoa (2006-2012) and Statoil (2008-2011) also participated in the IDDP-1 project in Krafla by direct financial and technical contributions.

In the first serious attempt to reach 4-5 km by well IDDP-1 at Krafla, NE-Iceland, in 2009, the well had to be completed at only 2.1 km depth after entering into >900°C hot magma of rhyolite composition. In order to produce from the >500°C hot contact zone of the magma intrusion, the well was completed with a cemented 9 5/8" sacrificial casing to 1950 m depth, inside a 13 5/8" production casing to the same depth. A 9 5/8" slotted liner reached from 1,950 m to 2,072 m depth, with a barefoot 12 ¼" well from there to 2,096 m depth. Subsequently, during a two year-long flow test, well IDDP-1 became the world's hottest producing geothermal well, with a wellhead temperature of 450°C, flowing dry superheated steam at high pressures (40–140 bar). Production tests indicate the well IDDP-1 was capable of producing up to 36 MWe depending on the design of the turbine system. Series of pilot tests for power production were undertaken during and after the flow tests yielding breakthrough results in dealing with a magma within a geothermal system. First of all, (i) the IDDP project managed to drill into molten rock at >900°C and get out of it; (ii) it produced high permeability by hydrofracking the contact aureole rocks with cold drilling fluid; (iii) it managed to insert a protective casing (sacrificial casing), cement it in, and a liner; (iv) it produced superheated dry steam from the contact aureole at world record temperature for a geothermal well; (v) it showed that hostile fluid chemistry could safely be dealt with by steam treatment, enabling the steam to be taken directly into conventional steam turbines, and finally, (vi) it proved beyond reasonable doubts that world's first Magma-EGS system had been created, apparently confirmed by an injection tracer test after the discharge tests. While it would probably be more economical to use the steam directly from a well like IDDP-1 in superheat form, the process could evidently be reversed by using such wells for injection in an attempt to enhance the performance of the conventional geothermal system above. The IDDP-1 well had to be cooled down rather abruptly in 2012 due to valve failure and the pilot studies and flow test terminated. Many technical hurdles were met during drilling and the subsequent flow test of the IDDP-1 well and the lessons learned so far are very valuable for the continuation of the IDDP R&D program. We believe that proper engineering and geoscience carry the keys to breakthrough results in future utilization of high enthalpy geothermal systems worldwide. Preparation is well underway for the drilling and testing of well IDDP-2 at Reykjanes, SW Iceland, which is expected to be followed by IDDP-3 at the Hengill volcano before 2020.

1 INTRODUCTION

The January special issue 2014 of Geothermics was dedicated to Icelandic Deep Drilling Project (see also www.iddp.is). It contained 15 papers and mostly dealt with the borehole IDDP-1, the first IDDP hole in Iceland. It was drilled at Krafla in 2008 and 2009, and as is well known, ended in magma at 2,100 m depth, with a temperature of 900-1000 °C. Drilling into magma is a rare occurrence elsewhere in the world but instead of inserting a concrete plug in the bottom of the hole as was done in a similar situation in Hawaii (Teplow et al., 2008), the IDDP collaborators decided to investigate the hole further by lining it with a sacrificial casing, which was cemented in to 1,950 m depth but kept open (perforated) in the bottom section closest to the magma. Then the hole was allowed to heat slowly and eventually allowed to flow superheated steam for the next two years until July 2012. Throughout that time various investigations at utilizing this resource were carried out and some of the results described in the 2014 Geothermics Special Issue on IDDP. The success of this drilling and research was very rewarding, and might in the near future lead to a revolution in exploitable energy efficiency of high-temperature fields around the world. The IDDP-1 well had to be cooled down rather abruptly in 2012 due to valve failure and the pilot studies and flow test terminated. Many technical hurdles were met during drilling and the subsequent flow test of the IDDP-1 well and the lessons learned so far are very valuable for the continuation of the IDDP R&D program. As the drilling into magma was quite a challenge a closer description of the drilling operation is given in the next chapter.

Preparation is well underway for the drilling and testing of well IDDP-2 at Reykjanes, SW Iceland, which is expected to be followed by IDDP-3 at Hengill. A location map for the Krafla, Reykjanes and the Hengill geothermal fields is show in Figure 1.

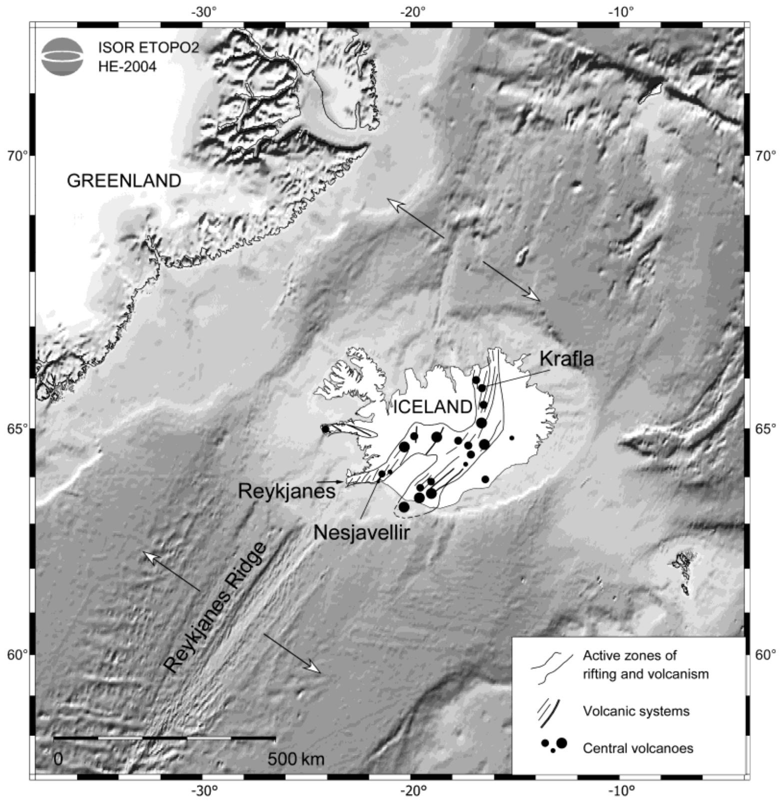

Figure 1: The location of Reykjanes, Hengill (Nesjavellir) and Krafla volcanic systems within the active rift zone in Iceland, where the IDDP will carry out 4.5-5 km deep drilling in three succeeding wells. Iceland is located on the Mid-Atlantic Ridge and owes its sub-aerial presence to an underlying hot spot or mantle plume.

Already there are several remarkable achievements by IDDP-1, mostly described in the Geothermics special issue 2014, but worth listing here. Firstly, (i) IDDP was able to drill down into the molten magma and control the well, despite some difficulties. Secondly, (ii) pumping cold water into the hole to break up the rock next to the magma created high permeability by hydrofracking. Apparently that connected the hot metamorphosed contact aureole above the magma chamber to the colder geothermal environments above. Thirdly, (iii) we were able to set steel casing down to the bottom of the hole, undertake balanced cementing and keep the 100 m bottom section open by a perforated liner. Fourthly, (iv) allowing the hole to blow superheated high-pressure steam for months at temperatures up to 450 °C set the world record for the hottest geothermal well in the world, and one of the most powerful. According to the measured output the available power was sufficient to generate up to 36 MW_e, which can be compared to the installed electrical capacity of 60 MW_e in the Krafla power plant. Fifthly, (v) we successfully demonstrated the capability of coping with the difficult chemical composition of steam from IDDP-1 by using simple counter measures. Sixthly, (vi) we demonstrated that the steam could be taken directly into the existing power plant at Krafla, and the field operator was preparing such an action just before the hole had to be closed due to a valve failure. Seventh (vii) and last but not least, by successfully drilling the hole and carrying out various experiments, we here claim to have created the world's first Magma-EGS system by the IDDP-1, demonstrating that a high-enthalpy geothermal system can be created in this way. That warrants some closer look at the IDDP-1 experience in succeeding chapters.

In various parts of the world EGS geothermal systems (Enhanced or Engineered Geothermal Systems) are being created by pumping cold water into hot dry rocks at 4-5 km depths. Then the heated water is taken up again as hot water or steam from nearby production wells. In recent decades considerable effort has been invested in Europe, Australia, USA, and Japan, with uneven results and typically poor results. With the IDDP project we can claim to have created such an EGS system, the first system in the world that supplies heat so to speak directly from a molten magma. On a global scale this is a remarkable achievement. The hot and dry magma contact aureole rocks were fractured by cooling during drilling and a connection established to the overlying conventional geothermal system. Then the process was reversed by flowing the IDDP-1 hole, emitting hot fluids up through the hole which created low pressure condition around the bottom of the hole, attracting colder fluids (~350°C) from above to descend downwards into the hole and to be heated to temperatures up to 450°C.

2. THE IDDP-1 DRILLING AT KRAFLA

The IDDP-1 well was drilled in the Krafla Geothermal Field (Figure 1) in 2008–2009 by Landsvirkjun, the field operator. The well was designed to reach supercritical conditions at ~ 4.5 km, temperatures above 374°C and pressures above 22 MPa. The IDDP consortium was supposed to take over the well fully cased at 3.5 km and deepen it to 4.5 km. Despite several setbacks the drilling progress was more or less according to schedule down to around 2,000 m when drilling became really challenging, including becoming stuck twice, first at 2,094 and then at 2,095 m depth, both followed by twist offs and subsequent side tracking. Finally, drilling was ended at 2,096m depth in the third leg when drill cuttings of fresh glass indicated that we had drilled into a magma.

This had not been realized earlier, though suspected by some of the crew on site, as in all cases we had been drilling with total loss of circulation (>50-60 l/s). Once realized, and in view of the rigorous well design, the steering committee of the IDDP decided to complete and flow test the well rather than inserting a cement plug and abandoning it.

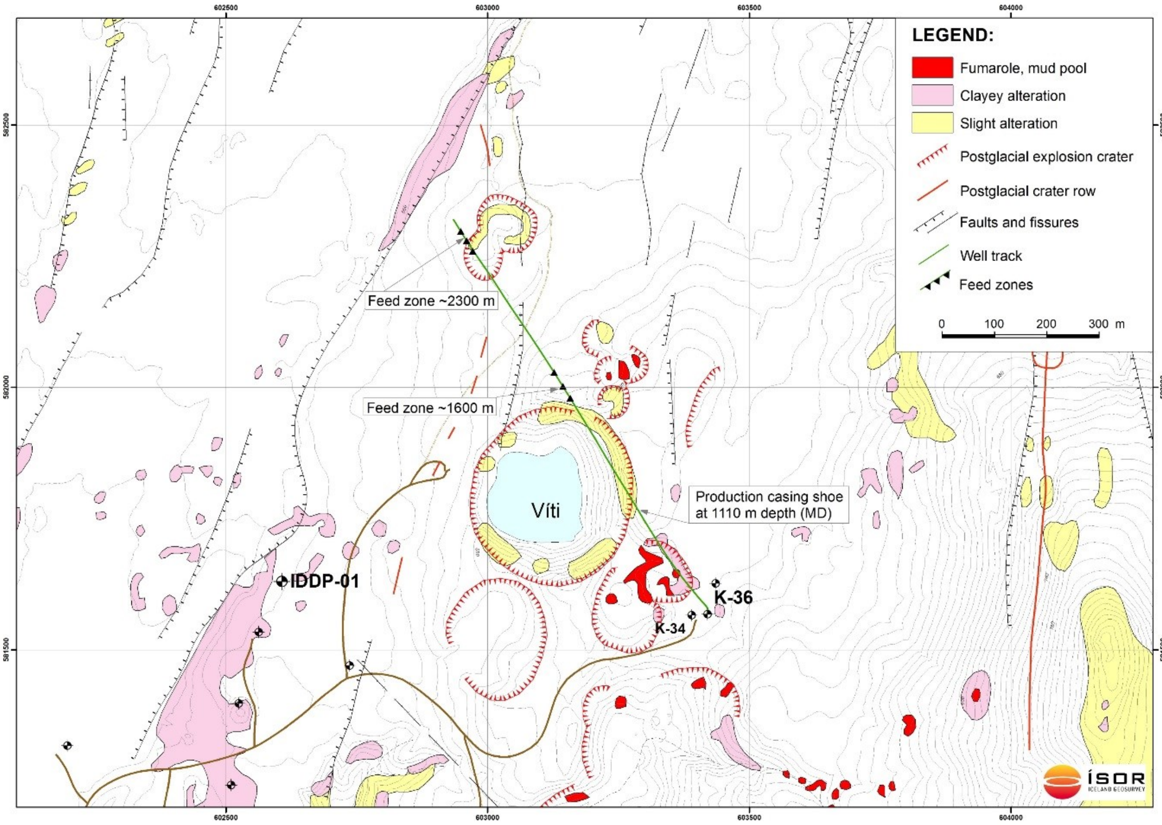

Figure 2: A geothermal/tectonic map of a part of the Krafla geothermal field showing the location of the vertical well IDDP-1. Also shown is the location of the inclined well K-36 and its track to the NW, where location of the main feed zones with in the production part are also shown (see further discussion in chapter 4).

The drilling procedure of IDDP-1 has been described in considerable detail (Pálsson et al., 2014, Sveinbjörnsson et al., 2010) so only some of it is repeated here. A short prolog on the reason for inserting an anchor casing much earlier than scheduled is discussed as well. The anchor casing was supposed to extend down to 2.4 km depth, to be followed by a production casing to 3.5 km depth, and then the well was to be finished to 4.5 km with 8 ½" bit and a 7" liner. Drilling for the 13 5/8" and 13 3/8" anchor casing was done with a tailor-made 16 ½" bit. Drilling progressed reasonably well to around 2,000 m although several unusual incidents occurred during drilling. At 1,432 m depth, for instance, circulation loss of 20 l/s was detected and a decision was made to cement off the loss zone to minimize the mud loss and to prevent interflow between loss zones during the casing procedure to follow. The retrieved bit turned out be in a surprisingly bad condition after only 47 m of drilling, and almost all carbides on the outer rows of the cones had broken off. Inserting a junk basket delivered only formation cuttings and a small amount of tiny metal fragments but no missing carbides. At that time, the well then appeared to be tight again so the cement plugging operation was skipped. Later, with BHA (bottom hole assembly) number 9 was RIH (run in hole) without a mud motor and drilled successfully to 1,907 m when the bit passed one million revolutions, a decision was made to POOH (pull out of hole) to change bit. Then only few carbides were missing off the bit but this time the stabilizers were badly worn with almost no hard facing left. Drilling commenced two days later with rather slow ROP (rate of penetration) due to hard formation. At 2,043 m total losses occurred (> 60 l/s) and, as the loss could not be healed, the mud was replaced with water. At 2,074 m depth, a box of an 8" drill collar twisted apart leaving a fish of 7 tons in the hole. The fish was successfully retrieved with an over-shot tool and a new BHA was run in hole. Four days later at 2,101 m, the torque was fluctuating and three singles were pulled out for reaming. The bit was run to bottom again where the torque increased significantly and the string was pulled back again. Three singles were pulled out and when pulling the last single the weight dropped by 20 tons and standpipe pressure decreased as the BHA was broken, leaving a fish in the hole for the third time. The bit was at 2,087 m depth and the top of the fish was at 1,999 m. After six days of unsuccessful fishing, the over-shot could not be disengaged and an explosive charge at 2,056 m was used to cut the string at the connection of the cross-over sub (XO) between the 8" and the 9" collars. One further attempt was made to fish the remaining 32 m of BHA before a decision was made to place a cement plug some 100 m above the fish and side track. After three attempts, side tracking was finally successful at 1,934 m depth. At this point in time well conditions had become somewhat complicated. Loss of circulation and unstable and washed out wellbore made the hole cleaning difficult. A decision was made to modify well design and set the anchor casing to 2,000 m rather than the targeted 2400 m. For safety reasons, this would mean that IDDP might have to decide to decrease the depth of the production casing schedule for 3.5 km, as well as the total depth. Drilling was stopped at 2,005 m depth when wellbore conditions were becoming critical again, and the anchor casing sunk in. The casing consists of two sections of different casing types, top 300 m consisting of ø13$^5/_8$" 88 lb/ft T95 with Hydril/Tenaris 563 threads, and the remaining lower part with ø13$^3/_8$" 72 lb/ft K-55 with Hydril/Tenaris 563 threads. As the bottom of the hole was considered critically unstable and fill expected to be up to 40 m, the casing shoe was set at 1,949 m and 24 m above the shoe was a stab-in float collar. Because of known losses in the well it was planned to cement it in two stages, i.e. an inner string job up to the loss zone at 1,600 m and back-fill up to surface through the kill-line. The cement slurry consisted of Dyckerhoff cement, 40% silica, retarder and a water loss agent, with density 1.9 kg/l. 80 m^3 of cement slurry were pumped through the cement string, followed by a dart to plug the float collar to avoid water washing the cement as the estimated water level in the annulus was 400 m. Temperature and cement bond logs (CBL) indicated top of cement at 1,600 m as expected. The second cement job required 100 m^3 but CBL and a temperature logs indicated top of cement at 100 m depth and no cement was in the annulus from 1,410 m and down to 1,600 m. The cement seems to have stopped at the feed zone at 1,360 m. Temperature below 1,600 m exceeded the limits of the logging tools.

Drilling for 9 $^5/_8$" production casing followed. Once the cement had been drilled out, the challenge ahead was to circulate the cuttings from the bottom with 12 ¼" drill bit in a 16 ½" hole. The plan was to drill the fill carefully with high viscosity pills with relatively low ROP and low pumping rate. Afterwards the pumping rate was increased and the string rotated and moved up and down. This process was repeated every 3 m of drilling until the bottom of the well was reached at 2,005 m. Cleaning by circulation was time consuming and difficult where spikes in the torque were frequently observed. At 2,016 m circulation was totally lost (>50 L/s). A decision was made to cement the whole of the 16 ½" section from the casing shoe at 1,957 m to the bottom at 2,005 m to avoid problems caused by lower circulating velocity in the larger diameter hole. A temperature log showed loss zones close to the bottom. Fiberglass pipes, designed for use in cementing plug jobs were used. Top of the cement was found at 1,892 m, 65 m inside the anchor casing, and the well was tight.

A decision was made to drill down to 2,040 m depth and then take a 9 m ICDP-NSF spot core for science studies, in a known fracture zone observed during the previous drilling attempts. The coring job started at 2,040 m but after only 2 m drilling in 3½ hours the drill string was POOH to inspect the equipment. The core bit was completely worn down, some inserts of the core barrel stabilizers were broken off and along the barrel the surface was marred by grooves. No core was in the barrel but the core catcher had been pressed approximately 70 cm up. Flaky chips of cement were found inside the core barrel triggering suspicion that the core catcher might have got stuck and unscrewed inside the barrel. The worn equipment indicated junk was in the hole and a 12 ⅛" mill tooth bit and a junk basket were sent downhole with the aim of drilling to 2,060 m. Milling continued despite total loss at 2,054 m. Formation fragments, small metal shavings and diamond fragments from the core bit were retrieved, along with abundant fresh rock fragments that were presumably pieces of broken core. Another attempt to stabilize the well was made by placing a cement plug in the well. The cement was drilled out and drilling in formation commenced at 2,060 m. Circulation losses became intermittent from 2,067 m and from 2,076 m total loss of circulation occurred.

At 2,103 m a sudden rise in torque was observed and the string got stuck for two minutes. The string was freed by pulling with 160 tons and one single was pulled out. After one and a half hours of circulation with several high viscosity pills, the string was carefully lowered to the bottom again. When the bit hit the bottom of the hole, torque suddenly increased again and the bit was pulled up 13 m (one drill pipe length) and few minutes later the torque increased again and the drill string was stuck. Almost immediately, the stand pipe pressure increased and circulation was blocked. The jar did not function and after 24 hours a decision was made to attempt a blind back off. The string was gradually torqued up (made up) to the joint between the lowest Heavy Wall Drill Pipe and the uppermost drill collar (DC) before a successful back off at the connection of the top sub of the Anderdrift tool. The fish left in hole consisted of the bit, 2 x stabilizers, 1 x 8" DC and the Anderdrift tool with the top of located at 2,072 m. A fishing BHA was RIH and connected to the Anderdrift tool and fishing was carried out for two days, with jarring and pulling, without any progress. A possible reason for the string being stuck was thought to be cement having caved in and therefore, two attempts were made pumping hydrochloric acid downhole to dissolve the possible cement. The acid was diluted to 25% and an inhibitor was added to protect the drill string and the connection on the top sub of the Anderdrift tool was disconnected for opening the string to inject the acid. Eventually, the drill string was backed off again and a second side track was planned.

Two attempts were needed to place a cement plug from the top of the fish at 2,072 m up to 1,927 m, 30 m inside the anchor casing, and several attempts were necessary before the side tracking was eventually successful, drilling in formation from 1,985 m. Torque and pressure fluctuated and big chips of fine grained basalt were observed on the shakers. One explanation of these unexpected returns is the long time with an open hole below the casing shoe and the formation, believed to be 340°C, had been cooled repeatedly, which may have resulted in thermal cracking. At 1,992 m it was decided to POOH and remove the mud motor from the drill string before drilling further to minimize the financial risk if the string would get stuck again. Drilling commenced again on June 23rd with rather low ROP and irregular loss of circulation until 2,071 m where total circulation loss occurred once more. After that, high viscous pills were pumped down twice on every single to keep the well perfectly clean before entering the troublesome zone at 2,100 m depth. On June 24th the string was pulled up into the casing after having drilled down to 2,100 m. A high viscosity pill was pumped down before running back down to bottom. The well was perfectly clean and drilling continued. At 2,096 m the ROP doubled (from 2 m/hr to 4 m/hr), the torque increased and the string became stuck and had to be pulled (125 tons) to free it. A single was pulled out and circulated for 1½ hours. The bit was run down to bottom again slowly and the torque increased again at the same depth as before and a single was pulled out again and held for few minutes. When running in again (2 m) the top drive and the single on the floor moved upwards and the weight decreased by 45 tons and immediately the string was stuck. The crew managed to maintain the circulation and the returns were pulsating at first, but in a short while it came steady for about 3-4 hours before it was totally lost again. No smell of H_2S gas was detected but the returns became red-brown in color and after that, abundant cuttings of quenched glass were observed on the shakers, indicating that magma had flowed into the hole. Circulation was maintained for 24 hours without moving the string before the string could be pulled loose. The bit proved to be in excellent condition and is now on display at Landsvirkjun headquarters in Reykjavik. Similarly no damage could be seen on the other parts of the BHA.

In summary, it is clear that we drilled into magma three times, the first two without really knowing, first at 2,094 m, then 2,095m and finally at 2,096 m below casing flange, or 2,102 m, 2,103 m and 2,104 m below the drilling rig deck. Figure 3 shows a drawing of the IDDP-1 well as built.

Further drilling into the magma was not considered feasible but the situation presented a unique opportunity to study more closely the magma contact aureole environment. The well was logged and the injectivity tested to decide what to do with the well. Initially, the injectivity index was close to 15 (l/s)/bar, but later decreased to 2.5 (l/s)/bar, a decrease which may relate to condensation of steam- to liquid-dominated environment upon cooling. As the well had been designed to withstand very high pressure and temperature conditions, Deep Vision, the IDDP steering committee, decided to attempt to produce from the well. To further secure the well, the project team decided to install the 9 $^{5}/_{8}$" production casing as a sacrificial casing to 1,935 m due to possible acidic fluid, and screw a 9 $^{5}/_{8}$" slotted liner from there to 2,072 m to maintain the wellbore open for flow testing. In order to cement the production casing above the open production zone, an annulus packer from Peak was set in the Ø9 $^{5}/_{8}$" casing just above the Ø13 3/8" casing shoe and above the packer a cementing stage tool. The plan was to inflate the packer and cement with an inner string through the stage tool to surface. Because of the circulation losses below the casing it was possible to maintain the well cool (temperature below 30°C) while running the annulus packer and the inner string and sealing cups. The cooling process would continue after the cementing job. The packer was inflated but failed to hold sufficient pressure and started to leak after several hours. When the rubber sealing cups, used to inflate the annulus packer and later to inject the cement through the ports on the stage tool, were recovered they showed signs of temperature damages. The options available were to pull the casing out of hole and order a new casing packer or do a balanced cementing job from surface, which became the procedure chosen. In the reverse cementing procedure the cement slurry forms a plug and displaces the water in the annulus leaving no water pockets between the two casings. By locating the water level in the well when pumping water at the same volumetric rate as the cementing, the balance in the well was found. Volumetric calculations assumed that the cement slurry would balance at 1,800 m. The bottom of the cement was not that critical but should ideally be within the range 1,700 to 1,950 m. It was critical that the cement did not reach the bottom as it would then cover the slotted liner section. While cementing the first phase with a standard high temperature blend, the pressure was logged in real time and the water level was controlled by adjusting the pumping rate inside the casing. A CBL-log on the following day indicated TOC (top of cement) at 725 m and the bottom of cement at 1700 m. As the TOC, when it balanced, is between the two casing strings after the reverse circulation cementing, the annular space from 725 m to surface was full of air (not water). The annulus was then back-filled to surface with Dyckerhoff cement as cementation phase 2.

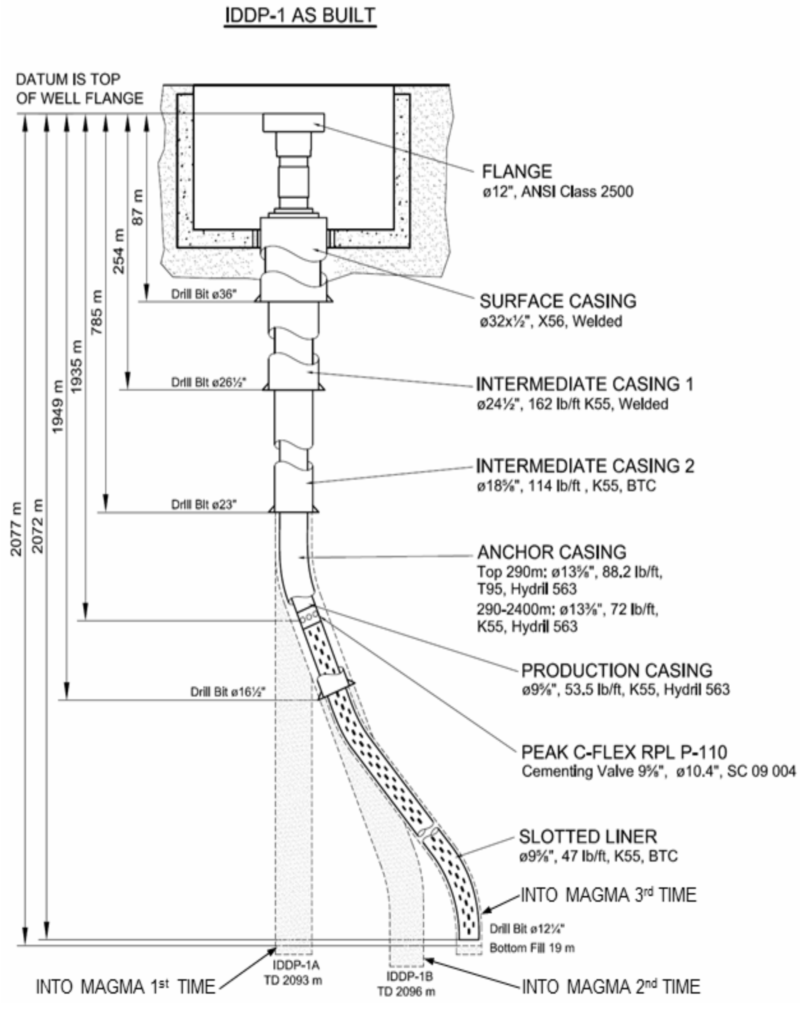

Figure 3: Drawing of well IDDP-1 as built.

As a final drilling operation, a 12” Class 1500 wellhead valve had to be replaced by a casing pack off and an expansion spool and a modified 10” ANSI Class 1500 master valve with 2500 class flanges. This work had to be carried out with the well open and was successful, the pumps only shut down for sufficient time for master valve replacement. The well was then closed on July 7th, 2009, and the rig prepared for demobilizing, but cold water was injected for 4 weeks before the well was eventually shut in for recovery.

The reader may wonder if the drilling history of IDDP-1 well, briefly summarized above, has been similar for other drillholes in Krafla. The answer to that is no, and moreover the IDDP-1 history is quite unusual. Conventional wells in Krafla are drilled by 12 ¼” bits for 9 5/8” production casings to 800-1,200 m, and 8 ½” finish to 2,000-2,500 m, with 7” perforated liner. An obvious difference to IDDP-1 concerns the well diameter 23 ½” bit and 16 ½” bit to similar depths respectively. The drilling of well K-25 (Guðmundsson et al. 2008) for instance, which is only 100 m away from IDDP-1, was more or less trouble free to 2,100 m, where the drill bit though got stuck, cut loose and the well finished in that condition without attempts to deepen it further. Another well, K-36, few hundred meters apart (see Figure 2), was also drilled with no trouble to speak of to 2,501 m depth (inclined) (Guðmundsson et al., 2008), with the main feed zones at around 1,600 m and around 2,300 m. The lower feed zone appeared to be superheated and was very powerful, and upon mixing with the upper two-phase feed zone at 1,600 m, became very corrosive. Therefore, in order to maintain production from this well, K-36, the deepest part of the well and the lower feed zone at 2,300 m depth was sealed off by a cement plug. Accordingly only the feed zone around 1,600 m was capable of returning to the surface a 2-NDS tracer that was later injected into IDDP-1, an observation of key importance to the main conclusion of this paper. The last example of reasonably trouble-free drilling in Krafla was in well K-39 (inclined) which apparently intersected magma at 2500 m depth (Mortensen et al., 2010), few months before the drilling of IDDP-1 began. The lower part of K-39 was sealed off with cement. In view of the general drilling experience at Krafla by more than 40 wells, we expect that a new IDDP type well designed to intersect magma at 2.1 km depth, with a deep production casing to 1.8 km depth, could be safely drilled and produced. In that case more conventional well diameters should be chosen, possibly with 9 5/8” casing to 1.8 km.

3. THE LITHOLOGY, ALTERATION AND RESRVOIR CONDITIONS IN IDDP-1

The lithology and alteration mineralogy in well IDDP-1 were studied in drill cuttings collected at 2 m intervals, and by down hole geophysical logs (Mortensen et al. 2014). The stratigraphy comprises basaltic lavas and hyaloclastite sequences extending down to 1,362 m succeeded by an intrusive complex. Intrusions comprise basaltic dykes, dolerites and below 2,020 m, granophyre and felsite intrusions. The intrusive rock intensity is quite high up to 40–50% of the stratigraphic column in most wells located within this geothermal field at similar depth. Rhyolite magma was intersected below 2,100 m.

The alteration mineralogy reflects cooling in the upper 1,500 m of the reservoir. Below 1,600 m temperature follows the boiling-point-depth curve (BPD curve). Alteration minerals are scarce in the vicinity of the feed zone at 2,035–2,080 m which may correlate with a superheated steam zone above the magma, but estimated bottom hole temperature is close to 500 °C. Apart from intersecting magma, the stratigraphy of IDDP-1 is pretty similar to the stratigraphy of neighboring wells (Guðmundsson et al., 2008 b, Ármannsson et al., 1987; Stefánsson, 1981). The high proportion of intrusive rocks encountered in Krafla wells may reflect the shallow depth to an underlying magma chamber. The magma chamber was detected from S-wave attenuation and reported as two elongated magma bodies at 3-7 km depths, observed during the Krafla fires – a volcanic episode in 1975–1984 (Einarsson, 1978).

The reservoir conditions in IDDP-1 are characterized by an upper reservoir with isothermal conditions at ~170 °C, but alteration mineralogy indicate that temperatures were close to the BPD curve in the past. The lower reservoir is characterized by temperatures following the BPD curve and is reflected in the alteration mineralogy by the absence of calcite, but a transition to the lower reservoir correlates to the dyke complex, in part pointing towards a decrease in formation porosity and permeability.

The estimated temperature of the magma encountered in IDDP-1 was around 900 °C, while composition of the melt points towards an origin through partial melting of hydrothermally altered basalts at depth (Elders et al., 2011; Schiffman et al., 2014; Zierenberg et al., 2013). The main feed zone at 2,035–2,080 m depth in the well is tied to the granophyre and felsite just above the rhyolite magma. Temperature recovery indicated that reservoir temperatures should approach 500 °C near well bottom, but the superheated zone relates to an interval in the well characterized by scarcity of alteration minerals. Schiffman et al. (op. cit) inferred equilibrium temperatures of 800–950 °C from coexisting clinopyroxene and orthopyroxene mineral pairs in mafic granoblastic rocks recovered immediately above the rhyolite intrusion. These high temperature metamorphic rocks constituted a conductive boundary layer for heat transport between the magma body and the overlying hydrothermal system. Heat flow across this boundary layer was calculated to be a minimum of 23 W/m^2. The size of the intrusive body and the extent of the conductive boundary layer are still unknown. Nonetheless, Schifmann et al., 2014, identified the conductive boundary layer at the bottom of the IDDP-1 borehole as a thermal “link” between the rhyolite magma and the overlying hydrothermal system.

Referring now to Mortensen et al., (2014), the pressure response during step rate injection tests two days after having drilled into in magma the third time was quite unusual and gave very high injectivity indices, 8-15 (l/s)/bar, which are much higher than have ever been seen before in Krafla wells. Recurrence of unusual changes during the injection tests seemed to indicate unstable reservoir conditions during the intensive injection of cold water (up to 70 l/s) in the vicinity of the magma. Repeated drilling into that zone repeatedly involved total loss of circulation, despite the inevitable assumption of very low permeability in the metamorphosed conductive boundary layer to the magma. Thus hydrofracking during cold water circulation during drilling and injection tests seems to be in evidence, or at least is the most like scenario to explain the total circulation losses in this zone and the unusual behavior during the injection tests. Upon further cooling of the boundary layer the injectivity indices lowered to more conventional values as shown in Table 1.

TABLE 1: Overview of injectivity indices from step rate tests before and after intersecting magma in IDDP-1. (MD: depth of logging, TD: depth of well, Q: flow rate, ΔP: change is pressure, II: injectivity index in (l/s)/bar).

Date	MD [m]	TD [m]	Q_1 [l/s]	Q_2 [l/s]	ΔP [bar]	II [l/s/bar]
5.6.2009	500	2060	19.6	40.1	6.3	3.2
10.6.2009	950	2103	20.0	30.0	6.0	1.7
26.6.2009	2050	2104	40.0	55.0	1.0	15
-	-	-	55.0	70.0	1.1	14
-	-	-	70.0	40	-3.8	8
27.6.2009	2050	2104	40.0	20.0	8.0	2.5
3.7.2009	400	2104	25.2	42.2	6.1	2.8
-	-	-	51.5	25.2	-11.9	2.2
7.7.2009	2050	2104	20.0	40.0	8.6	2.3

The drilling operation and associated injection tests was complete 7th July 2009, and after that some 25 l/s of cold water was injected until 11th August 2009. Thermal recovery of the IDDP-1 well then took a somewhat surprisingly long time, as revealed in Figure 4a, but relates to the fact that there was no internal flow within the well nor the surroundings. To begin with the heating was basically conductive from the well walls, reflecting the reservoir temperature adjusting to the BPD curve below ca. 1,600 m towards the bottom in about 2 months. After that thermal expansion and steam bubbles within the well explains the temperature increase above 1,600 m depth adjusting to a steep thermal gradient, while the upper reservoir temperature is about 170°C. The extensively cooled bottom part of the well thermally recovered in about 7 months. Once thermally recovered the well was ready for the first discharge test. Figure 4b shows corresponding pressure logs showing a pivot point at 155 bar at 1,950 m depth.

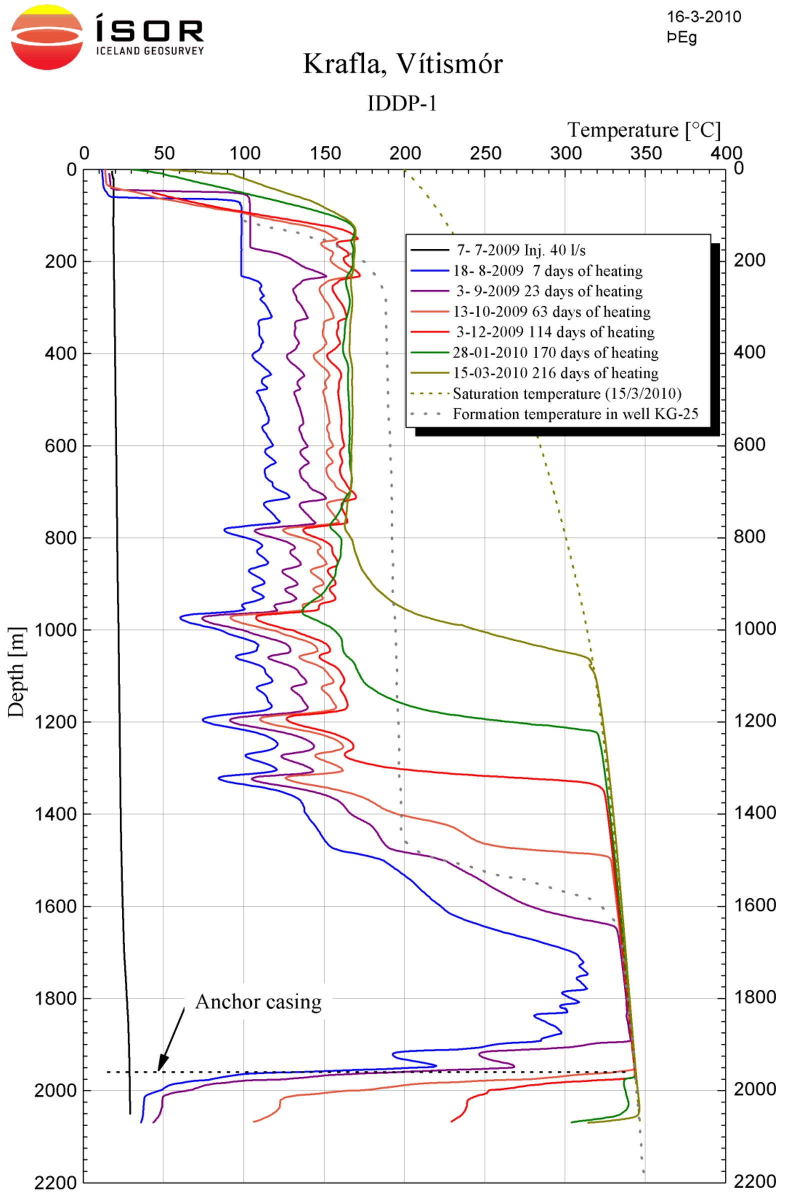

Figure 4a: Thermal recovery of IDDP-1.

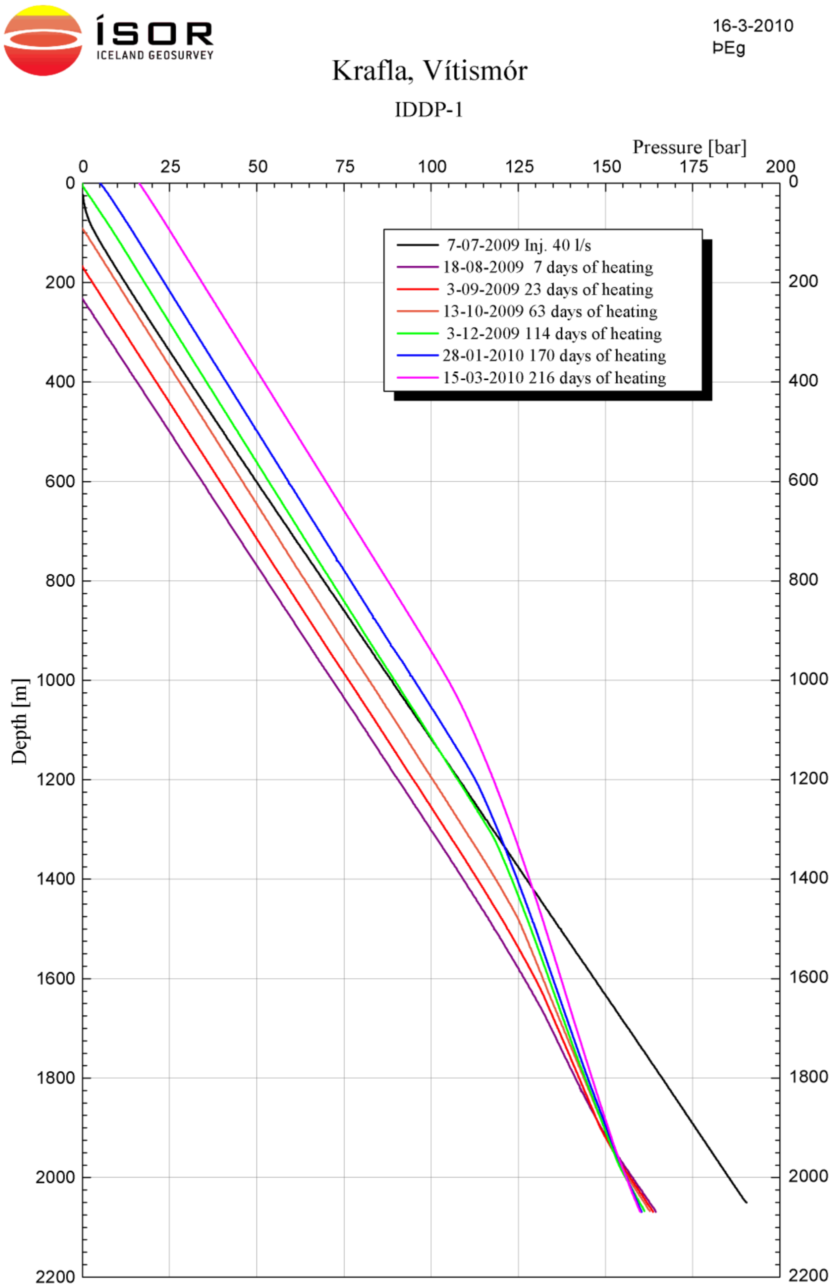

Figure 4b: Pressure logs during thermal recovery.

4. DISCHARGE AND PILOT TESTING OF IDDP-1

Discharge tests and pilot production tests undertaken in IDDP-1 during 2010 to 2012 are described in some detail by Ingason et al., 2014, and by Hauksson et al., 2014. The well was discharged during five successive time intervals, the 1st lasting for 10 days at flow restricted by the narrow flow line system, beginning 22nd March 2010. The 2nd discharge at full diameter flow lasted for more than 3 months, ending late August 2010. During the remaining three discharge intervals pilot tests were conducted, the 3rd discharge lasting for 9 days in May 2011, the 4th for 2 days in August 2011, and the 5th and last for about 10 months at restricted flow, from late September 2011 to late July 2012. During the last test the well discharged superheated steam at 450 °C and enthalpy approached 3200 kJ/kg. Shut in pressure was 150 bar, whereas a maximum flow in excess of 50 kg/s of superheated steam at 40 bar was measured. The power potential based on these tests ranged from 25-36 MW_e depending on the type of power generation cycles to be applied.

The results of the pilot testing will be described in detail by Markússon and Hauksson, 2015, and the earlier part of it was described by Hauksson et al., 2013, 2014. Here we like to highlight the most promising result of the conducted pilot tests, namely a wet scrubbing experiment mainly operated during the 5th discharge period. Prior to that we also like to refer to associated papers by Einarsson et al., 2015, discussing the odds and ends of operating a well like the IDDP-1 well, which had to be closed rather abruptly due to malfunction of some of the surface equipment, followed by a failure of a set of two 1500 class master valves which unexpectedly failed when really needed. The well needed to be killed by cold water, but despite a slow and careful injection the thermal strain on the 450 °C hot sacrificial casing was too severe. The casing snapped apart (pins out of boxes) at least at two depth levels above 600 m while the condition of the casing below that depth is unknown. Cold water is still being injected into the IDDP-1 well and will be so onwards until a suitable rig is moved into the field for investigating the damage closer and possibly repairing the well. In 2013 a major tracer test was conducted in the Krafla field. Different tracers were injected into 3 wells including the IDDP-1 well (Table 2). The tracer test is described in detail by Júlíusson et al., 2015. The result of the tracer test involving IDDP-1 is of key importance to this paper as discussed below.

The steam from IDDP-1, tested for many months at 140 bar pressure and 450 °C, contained 100 mg/kg HCl gas which forms hydrochloric acid upon steam condensation, and 62 mg/kg silica was dissolved in the steam phase, which began precipitating at pressures lower than 80 bar, increasing in rate with lowering pressures. In addition the steam contained gaseous sulfur, which formed sulfuric acid upon condensation. All this makes the steam unfavorable for direct use, and thus several tests were needed to mitigate the acid formation and corrosion as well as the silica scaling (Markússon and Hauksson, 2015). The superheated steam is inert within the wellbore so the mitigation process can be performed at surface, which is of importance to the operator. It was demonstrated that by scrubbing the steam with brine from the Krafla power plant, pure steam could be produced. For this, sufficient alkaline brine has to be available from other wells. Modification of the scrubbing process was then proposed in order to remove the silica and most of the acid by pre-scrubbing it with small amount of water and subsequently scrubbing it with alkaline brine. The small pre-scrubbed water stream would contain most of the silica particles, which could be disposed of separately. In essence, the hostile fluid chemistry of the superheated steam in IDDP-1 proved to be manageable with simple acid/base chemistry using the wet scrubbing method along with controlled pressure drop to remove solid silica.

Due this promising result, the field operator at Krafla was in the process of scaling up the scrubbing experiment, and had plans to hook the IDDP-1 well up to the steam gathering system later in the year 2012 for use in the existing 2x30 MW_e turbines, at 7 bar inlet pressure. The unfortunate failure of the IDDP-1 surface equipment evidently halted further implementation of this plan. In the near future, however, it is quite likely that the operator will address a similar plan again once the condition of the IDDP-1 well has been evaluated closer, and/or then possibly with a new well aiming for superheated steam at similar conditions.

An interesting information on the IDDP-1 bottom hole environment resulted from a tracer injection test that followed the abrupt cold water injection to control the well. Table 2 shows the type of tracers injected into 3 wells, K-26, K-39 and IDDP-1. The IDDP-1 tracer was retrieved in only 1 well, K-36, which has a feed zone at about 1,600 m depth within the two phase reservoir, as discussed above. The 2-NMS tracer first appear about 5 days after injection, peaked around 10 days after injection and vanished in a month (Figure 5). The implication and results of the tracer test are described in more detail by Júlíusson et al. 2015, but what is of importance to the IDDP-1 story is the apparent connection to the overlying conventional two phase liquid dominated system.

One of the unknowns about the IDDP-1 was the sustainability of a well producing superheated steam at 450 °C and very high pressures. Was the production sustainable or not? One possibility was that the well was only "producing" the heated cold water injected during and after drilling, and that the discharge would eventually diminish. However, a quantitative evaluation of the total water in and out of the system seemed to exclude that possibility and the well showed no signs of any decline during the extended discharge tests. So where was the water coming from? From the contact aureole itself or from above? Somewhat surprisingly, the CO_2 content in the superheated steam was surprisingly low, and even lower than CO_2 in the atmosphere, an information that might give a clue to its origin, i.e. if water was moving downwards towards the wellbore. But the tracer really came as a pleasant surprise, being detected in a neighboring well K-36, 600-700 m away (Figure 2). The tracer was detected after entering into K-36 through the 1,600 m feed zone, as the bottom section and deeper feed zones had earlier been sealed off by cement. If a tracer can flow up from the IDDP-1, which is only open at the lowest 100 m interval within the contact aureole, a fluid from above can obviously also flow downwards from the two phase reservoir, provided a low pressure regime is created at bottom of IDDP-1 during discharge, which evidently is the case. This seems to indicate that by IDDP-1 an EGS-magma system was created during discharge, meaning that a fluid at BPD conditions within the two phase reservoir flowed downwards and was heated by some 100°C from ~350 °C to 450 °C. So, tentatively we claim that by IDDP-1 we incidentally created the world's first magma-EGS system warranting the title of this paper. Is there a possibility that we are drawing a wrong conclusion? Evidently there is always such a possibility, e.g. if the well suffered a casing damage in 1-2 km interval. However as we have both the production casing to 1,930 m cemented, despite the lack of cement in the 1,410-1,600 m interval, and the sacrificial casing cemented in, we like to consider the possibility of a casing leak rather slim. Nevertheless, the IDDP-1 well needs to be investigated closer, with a drill rig for removing potential blockages and proper down hole monitoring tools. Hopefully the IDDP-1 well can be reconditioned for further testing and eventual steam production.

TABLE 2: Tracers injected into three well in Krafla in 2013 (From Júlíusson et al 2015)

	KG-26	KJ-39	IDDP-1
Naphthalene sulphonate	2.7-NDS	2.6-NDS	2-NMS
Alcohol	Ethanol	Methanol	
Perfluorocarbon	PDMCH	PMCH	PMCP

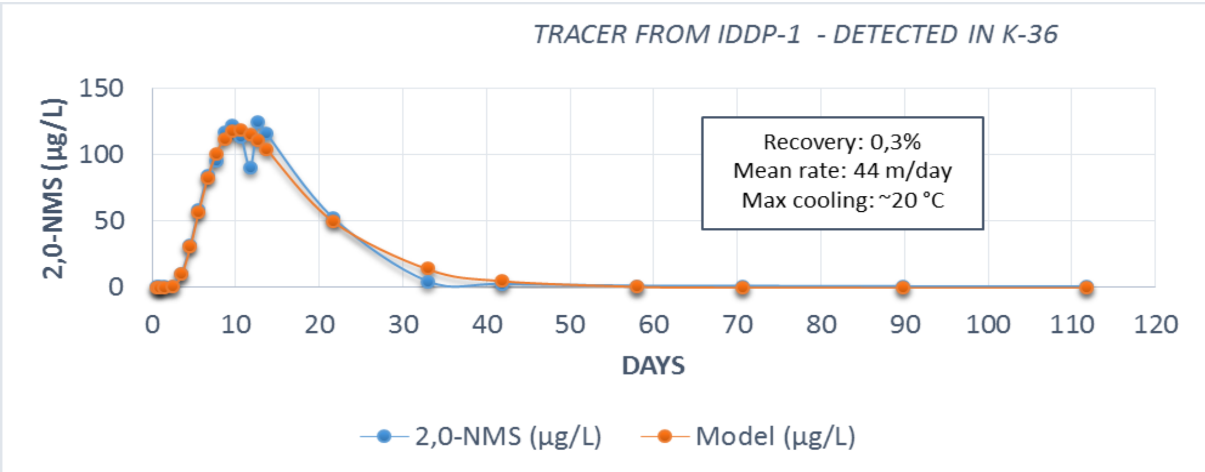

Figure 5: 2-NMS tracer injected into IDDP-1 recovered in well K-36 which only has a feed zone at about 1,600 m depth (data from Júlíusson et al 2015).

5. DISCUSSION

What will the future be like and do the IDDP results so far have a practical value? We envisage a bright future and like to answer the question positively. Although the IDDP-1 hole is unusable at the moment the aim in the near future should be to drill a similar hole and/or to repair the IDDP-1 hole. The experiment in Krafla suffered various setbacks and tried personnel and equipment throughout. However, the process itself was very instructive, and apart from scientific results published in Geothermics 2014, comprehensive reports on practical lessons learned have been completed and the work continues. The lessons learned will be applied by Landsvirkjun at Krafla in the future, and the IDDP program is benefitting from it by having already modified the design of both the flow test equipment and the design of the next borehole, IDDP-2 (Ingason et al. 2015, Óskarsson et al., 2015) which is scheduled to be drilled at Reykjanes in 2015, or within the next years in the event of unforeseen delays. While it would probably be more economical to use the steam directly from a well like IDDP-1 in superheat form, the process could evidently be reversed by using such wells for injection in an attempt to enhance the performance of the conventional geothermal system above. The implication from the IDDP-1 experience for high-temperature geothermal systems worldwide and their utilization has been discussed broadly by Elders et al., 2014, basically stating that what can be one in one place can be repeated in another. We believe that proper engineering and geoscience carry the keys to breakthrough results in future utilization of high enthalpy geothermal systems worldwide.

6. CONCLUSIONS

The first serious attempt to reach 4-5 km depth into a supercritical reservoir by well IDDP-1 at Krafla in 2009, had to be terminated at only 2.1 km depth after drilling into >900°C hot magma of rhyolite composition. In order to produce from the >500°C hot contact zone of the magma intrusion, the well was completed with a cemented 9 5/8” sacrificial casing to 1,950 m depth, inside a 13 5/8” production casing to the same depth. A 9 5/8” slotted liner reached from 1,950 m to 2,072 m depth, with a barefoot 12 ¼” well from there to 2,096 m depth. Subsequently, during a two year-long flow test, well IDDP-1 became the world’s hottest producing geothermal well, with a wellhead temperature of 450 °C, flowing dry superheated steam at high pressures (40–140 bar). Production tests indicate the well IDDP-1 was capable of producing up to 36 MWe depending on the design of the turbine system. A series of pilot tests for power production were undertaken during and after the flow tests – yielding breakthrough results in dealing with a magma within a geothermal system. First of all, (i) the IDDP project managed to drill into molten rock at >900°C and get out of it; (ii) it produced high permeability by hydrofracking the contact aureole rocks with cold drilling fluid; (iii) it managed to insert a protective casing (sacrificial casing) and a liner; (iv) it produced superheated dry steam from the contact aureole at world record temperature for a geothermal well; (v) it showed that hostile fluid chemistry could safely be dealt with by steam treatment, enabling the steam to be taken directly into conventional steam turbines, and finally, (vi) it proved beyond reasonable doubt that world's first Magma-EGS system had been created, apparently confirmed by an injection tracer test after the discharge tests. The IDDP-1 well had to be cooled down rather abruptly in 2012 due to valve failures and the pilot studies and discharge tests terminated. Many technical hurdles were met during drilling and the subsequent flow test of the IDDP-1 well and the lessons learned so far are very valuable for the continuation of the IDDP R&D program. Preparation is well underway for the drilling and testing of well IDDP-2 at Reykjanes, SW Iceland, which is expected to be followed by IDDP-3 at Hengill before 2020.

IDDP-1 being discharged in August 2012. Note the superheated steam at the top of the rock muffler (p. Kristján Einarsson).

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