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

The IDDP-2 DEEPEGS Drilling Experience and Lesson Learned

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Keywords: IDDP-2, Drilling, Coring, Cementing, DEEPEGS

ABSTRACT

The drilling of the deepest high-temperature geothermal well in Iceland, IDDP-2, was completed at 4,650 m depth in January 2017. The well is inclined below 2.75 km depth so true vertical depth is closer to 4.5 km below surface. Drilling began by deepening an existing 2.5 km deep well, RN-15 to 3 km depth, and case it with 9 7/8"– 9 5/8" casing and cement it to the surface by reverse cementing method. To reach the main up-flow zone of the Reykjanes system it was necessary to build inclination from 2.75 km with an azimuth of 210°deg. Below 3 km depth total loss of circulation was experienced to the end of drilling. A 7" perforated liner was run into hole and then a 7" production (sacrificial) casing to 1,300 m and cemented to surface. This was followed by running in a 6" rotary assembly to drill out casing shoes for the sacrificial casing and the liner. A 6" pilot hole, 8 m long, was then drilled before pulling out for running in 3 successive 6" coring tools to final depth.

The well was left with 3 ½" drill pipe to 4,590 m for long term stimulation and tracer injection. Several lessons learned from the drilling operation are addressed in the paper. To name a few, we recommend not to directionally drill such deep wells, as it involves all sort of problems with increasing depth, and increased risk of failure. This was well known before we began the drilling of IDDP-2, so other reasons ruled. Necessity to reach the center of the up-flow zone at Reykjanes called for our decision to directionally drill IDDP-2. The biggest problems in our drilling related to keyholes that kept the string stuck for days damaging several drill pipes. Next to mention, is the mitigation we used for cleaning the well by bleeding HT polymer and Guargum continuously while drilling, basically using cold water as drilling fluid throughout the drilling. The polymer helped greatly keeping the well clean and the standpipe pressure much lower than by drilling with pure water alone. In the paper we attempt to analyze the coring problems we had in the 8 ½" section. Coring with 8 ½" core bit and 7 1/8" core barrels was presumably far too stiff BHA for smooth run into 8 ½" inclined bore hole, and slimmer tools like the 6" core bits on 4 ½ core barrel like we used in the end is recommended. Our experience shows that cooling of superhot wells during drilling does not appear to be a problem, provided sufficient cooling fluid is available on surface for continuous cooling. Total loss of circulation throughout such drilling as ours, evidently calls for a rich surplus of cooling fluid. Good example of cooling efficiency was seen from the LWD logging tool below 4,000 m, which we tripped in at the end of drilling never experiencing more than 50-60°C heating, in an environment over 500°C hot. Cementing and casing integrity is and will be one of the most sensitive and risky part of a drilling operation for endurance. In the paper we address this sensitive issue and provide some advice for our future deep drillings.

1. INTRODUCTION

The Iceland Deep Drilling Project (IDDP) is a Research and Development project initiated by an Icelandic energy consortium in 2000 (www.iddp.is). It´s main goal is to find and investigate the economics of deep, high-enthalpy geothermal resources at supercritical conditions at 4-5 km depth by drilling holes into 400-600°C hot supercritical hydrous fluid (Friðleifsson et al., 2017, 2018). The main purpose is to find out if it is economically feasible to extract energy and chemicals out of such a system. The first formal well, IDDP-1, was drilled in Krafla, NE Iceland, in 2008-2009. That well was planned to be drilled to 4.5 km but incidentally was drilled into magma at 2.1 km depth which terminated further drilling at that time. However, IDDP decided to flow test the well and perform pilot tests by inserting a cemented sacrificial casing with an open perforated liner near the bottom. A most valuable pilot study followed on production from the contact aureole of the magma (Pálsson et al., 2014, Hauksson et al., 2014, and other papers in Geothermics, Special Issue on IDDP, V 49, 2014). The bottom line was that by testing IDDP-1 the world's first Magma-EGS system had been created (Fridleifsson et al., 2015). Lesson learned and experience from the IDDP-1 well was used in designing the second well, IDDP-2, to be drilled at Reykjanes in 2016 (Ingason et al. 2015). Originally the plan was to drill a new well, but later the drilling plan for IDDP-2 was modified to deepen an existing production well, RN-15, at the north side of the Reykjanes geothermal field. Well RN-15 had been drilled vertically in 2004 to 2,507 m depth, with a production casing set to 794 m and open hole below that. Final preparation for the IDDP-2 drilling began December 2015 and the drilling itself in August 2016. In December 2015, the plans for the IDDP-2 had been accepted as a part of European Union Horizon 2020 project called DEEPEGS (Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business, www.deepegs.eu). By that time an agreement had been reached with Statoil (now Equinor) to participate in the IDDP consortium to 2020.

The IDC drill rig Þór (Thor), 350Hp Bentec rig, was used for the drilling of the well. Well RN-15 was disconnected from the piping system to the power plant in June 2016 and the drill pad subsequently prepared to accommodate the large rig Thor, which was mobilized by late July 2016 and ready to spud in the 11th of August 2016. Figure 1 shows the drill rig on site.

Figure 1. Drilling rig Thor at the RN-15/IDDP-2 drill site at Reykjanes (photo TBW)

2. WELL RN-15 AND MODIFICATION FOR IDDP-2

Well RN-15 was drilled vertically to 2,507 m depth in 2004. The production casing 13 3/8" was landed at 794 m (from ground level) and the well was left as an open hole (barefoot), i.e. not supported by a perforated liner. Circulation losses had been relatively small during drilling, until at 2,395 m when a total loss of circulation fluid was observed for a while. At well completion the injectivity index was estimated close to 3.5 (kg/s)/bar or just below the reference limit of 4 (kg/s)/bar for a production wells at Reykjanes. Consequently, the well was stimulated at the end of drilling by heating and cooling cycles and that improved the injectivity slightly or up to 4.5 (kg/s)/bar. The well was then connected to the power plant in 2006. Its output capacity was moderate to low compared to the better producers, and before it was closed for deepening its production corresponded to about 2-3 MW_e (Friðleifsson and Sigurðsson, 2016).

An early IDDP-2 well design had been made by Mannvit consulting engineers and introduced at the WGC-2015 (Ingason et al., 2015). Once it was clear that HS Orka was to provide the production well RN-15 for deepening as IDDP-2, an immediate modification on the well design was needed. Table 1 shows the essential design details for each drilling phase, and a design diagram showing the well as built in Figure 2.

Table 1 Drilling, casing and cementing program

	Conductor	* (Phase 0) Surface Casing	*(Phase 1) Intermediate Casing I	*(Phase 2) Intermediate Casing II	(Phase 3) Anchor Casing	(Phase 4) Production Casing	(Phase 5) Perforated Liner
Well dia (inch)	Dug	26"	21"	17 ½ "	12 ¼ "	8 ½"	8 1/2"
Well depth (MD in meters)	~ 7	87	293	798	~3000	~5000	~5000
Well depth (TVD in meters)	~ 7	87	293	798	3000	~5000	~5000
Casing specs	28"	22 1/2"	18 5/8"	13 3/8"	9 7/8" & 9 5/8"	7"	7"
Weight		117lb/ft	96,5lb/ft	68lb/ft	42,8/47 lb/ft	26 lb/ft	26 lb/ft
Grade	API LP	X-52	K-55	K-55	T95/L80	TN 80HS	L80
Threads	Welded	Welded	Welded	BTC	GeoConn	TSH	BTC
No. of joints	~1	~8	~25	~69	~260	~110	~175
Cementing method	Cemented by Civil Contractor	Cementing Head	Stab in	Stab in	Reverse	Cementing Head, packer and port	
Drilling fluid	N/A (Dug)	Air and foam	Water based Bentonite	Water based Bentonite	Water with high visc. sweeps	Water with high visc. sweeps	Water with high visc. sweeps
Max. predicted temp	NA	100°C	150°C	260°C	~300°C	> 400°C	> 400°C

2.1 DRILLING PLAN

The plan was to deepen well RN-15 to be identified onwards as RN-15/IDDP-2, in order to keep the original data base ID number. After slowly cooling the well down, the first drilling operation was to deepen it from 2,500 m depth, with 12 ¼" rotary assembly, to about 3,000 m. An anchor casing (9 7/8" and 9 5/8") should follow and be cemented to surface. Thermocouple cables, from surface to about 2,700 m, a strain gauge (0–26 m) and a fiber optic cable (0–900 m) were to be strapped to the outside of the anchor casing string. An inclination to about 20° max, was to be built up for southwestward drilling (210°) from a KOP at 2,750 m depth. 20° inclination should be reached at about 3,100 m depth (MD). From 3,100 m Azimuth and Inclination should be kept (Hold drilling). The plan was to have the MWD tool in the drill string during the Hold section until its temperature limit was approached. The plan was then to drill to target depth of 4,500 m to 5,000 m with a conventional hold assembly, preferably including high temperature downhole motor. During the drilling from ~ 3,100 m depth to the bottom, around 15-20 spot cores were planned to be drilled at regular intervals. A 7" perforated liner was then planned to be set from 2,970 m to TD. Thereafter 7" production casing (sacrificial casing) to be RIH from top to about 1,300 m depth, and cemented in. The drilling operation was to be completed by RIH with 3 ½" drill string which should be left at bottom for post drilling soft hydraulic stimulation. Estimated overall timing for the drilling operation was 151 days. The drilling schedule was based on normal drilling operations, excluding rig mobilization and rig demobilization. Unexpected maintenance stops of the rig and other non-productive time where not included in the drilling schedule.

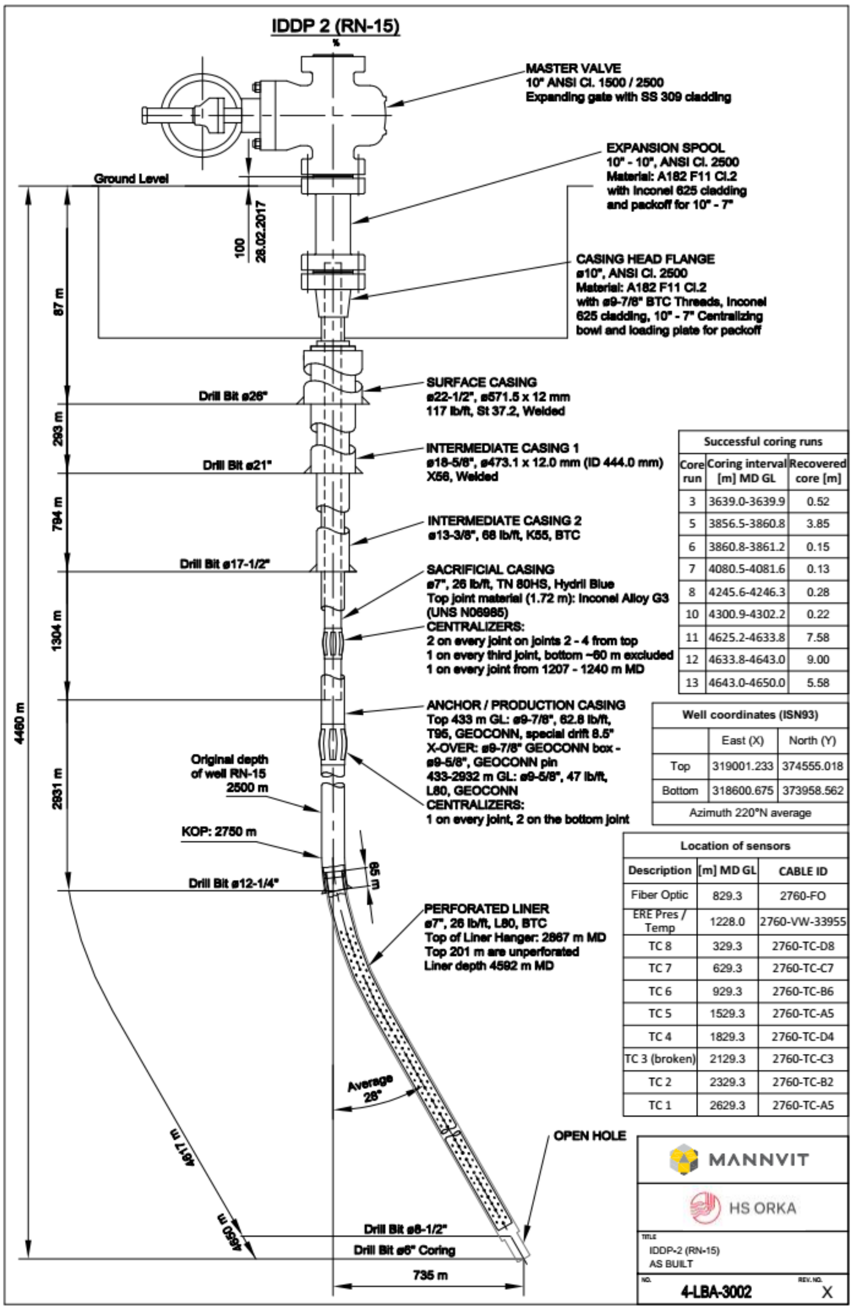

Figure 2. RN-15/IDDP-2 as built diagram. Information on the location of thermocouples from Petrospec, and depth intervals of coring attempts are also shown in the diagram and discussed in text.

2.2. DRILLING OF IDDP-2

The rig was ready to spud in 11th August 2016. While inserting tools a casing bulge was detected at 140 m depth which called for an inspection with a camera (Figure 3). It turned out to be necessary to use 12 ¼" milling bit and mill out the bulge between 141 m to 158 m, followed by an inspection down to the casing shoe to ensure there were no further obstructions in the casing. This was followed by a wiper trip with a new BHA (Bottom Hole Assembly) to 2,500 m.

The static water table in the well and the geothermal reservoir was at about 700 m depth, and within the production section some 8 loss zones were known in the well. Medium size loss zones were at 1,680 m and 1,720 m depths while the largest feed zone was at 2,360 m depth. In view of this total loss of circulation water was to be expected and experienced from the very beginning of the deepening operation for the production casing. Accordingly, no drill cuttings were retrieved from this section down to 3,000 m. At KOP (kick-off-point) however, we drilled into an opening at around 2,750 m which had to be cemented to solve cleaning problem. Cement was drilled out between 2,753-2,776 m and the well cleaned and drilled to 3,000 m. Following this the 9 7/8" – 9 5/8" casing string was inserted. Cables with 8 thermocouples from Petrospec, were attached to the outside of the casing string. The thermocouples were rated to tolerate up to 600°C. They were expected to enable continuous measure of temperatures at 341 m, 641 m, 941 m, 1,541 m, 1,841 m, 2,141 m, 2,341 m and 2,641 m depths (listed in Figure 2). The thermocouple at 2,141 m was damaged during the insert of the casing and due to that, and in order to try to prevent further damage of the cables along the casing, the casing was landed at 2,941 m. In addition, a pressure/temperature sensor was installed at 1,241 m depth, and a fiber optic cable to 841 m depth for temperature, and acoustic logging, was installed by GFZ Potsdam. Data from the thermocouples were used to evaluate the progress of the cementing operation (see figs. below).

Figure 3. The photo shows the bulge in RN-15 at 140 m (from camera run August 12th, 2016).

To cement the 2,941 m long casing string a reverse cementing method was used (RCC). The cement was pumped through two kill-line inlets with a pumping rate of 1.5 m^3/min to begin with, slowed down 0.5 m^3/min after 80 m^3, and then further down to 0.25 m^3/min. Two pumping units where used and a premixed cement slurry of 40 m^3. Total amount of cement slurry was ~150 m^3. After several hour delay from morning September 5th the cementing operation began at 22:40 in the evening and was completed at 3:00 on September 6th, with a fill up from 9:00-12:00 in the morning. This was followed by two runs of cement bond logs (Figure 4) The cement quality was different from the first cement batch (landed from ca 1,400 m to the bottom), which was premixed with a retarder, whereas the later batches was without any retarder. The reason for premixing the retarder in the first cement batch related to a pre-drilling model calculation of expected temperature recovery in the newly drilled well section from 2.5 km to 3.0 km depth. However, due to extensive circulation losses down to 3 km depth that resulted in good cooling of the well walls this pre-mixing of the cement should not have been done as it seriously delayed cement hardening in the bottom section. While there was truly cement everywhere behind the casing after the cement job this delayed hardening time shows up in the CBL logs (figure 4). There was also one depth interval in particular, between 2.3-2.4 km, which may have been deficient in cement or too cold to induce cement hardening during the logging. One of the Petrospec cables at 2,341 m (see Figure 5) did not show any heating during this time and reveals trustworthy temperature reading comparable to the downhole temperature logging during the CBL log. Later a casing damage was discovered in this depth interval 2,307-2,380 m. In retrospect – this may possibly relate to poor cementing coverage or loss of cement to the feed zone in this interval and thereby easier access of hot reservoir fluid in the several occasions the casing could temporarily heat up during the drilling and stimulation operation.

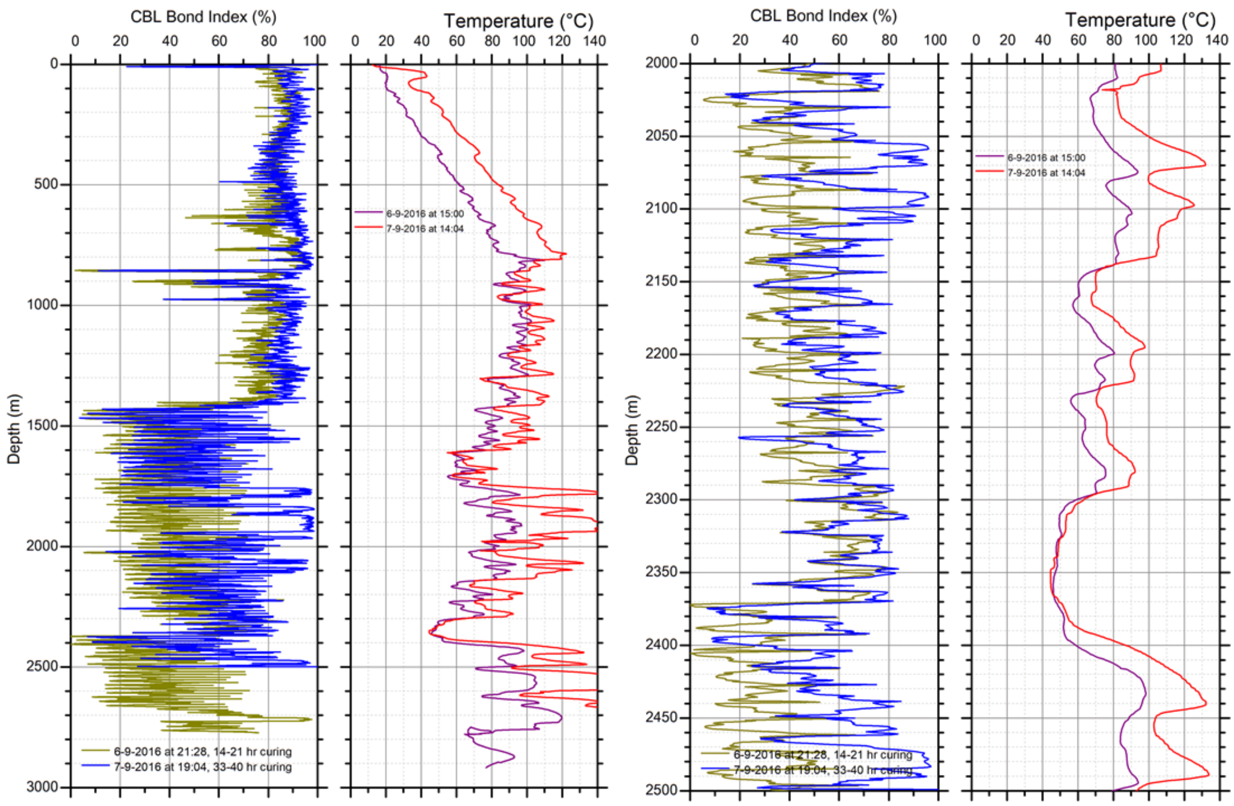

Figure 4. Two Cement Bond Log (CBL) profiles taken on September 6 and 7, 2019 after more than 14h and 33h curing time, respectively. On the left logs from the whole casing and to the right zoomed in on the interval 2000-2500 m. Notice the temperature logs as well, and the difference between the CBL curves above and below ~1.400 m depth. A retarder was pre-mixed in the slurry below ~1,400 m. Note also the 50°C hot interval at 2300-2400 m depth, not heating up between runs.

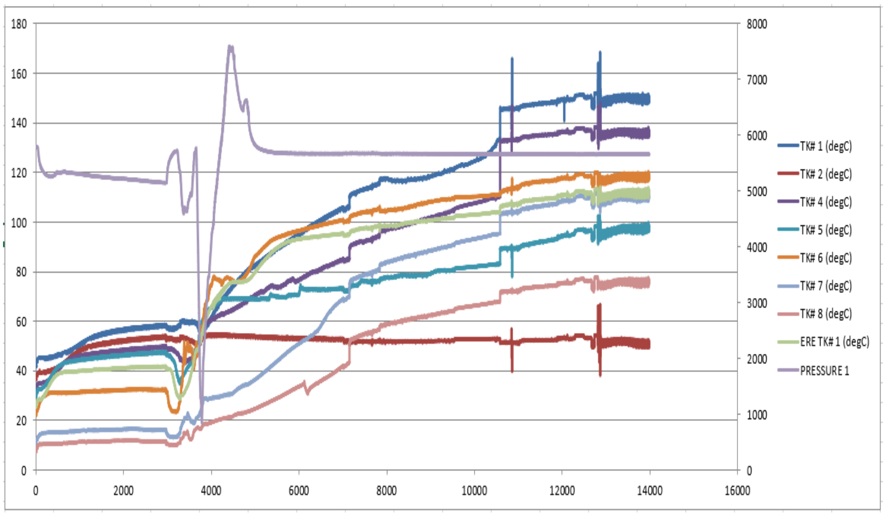

Figure 5. The Petrospec continuous temperature logs all show heating after cementing except thermocouple TK#2 which is at about 2340 m depth, closest to the main feed zone at 2360 m depth in RN-15.

On September 8th the casing was cut, Blow Out Preventers (BOP´s) nippled down and the previous casing flange cut off and a 10" ANSI 2500 flange mounted on the 9 7/8" casing. After BOP´s nipple up, followed by a pressure test, the 8 ½" rotary assembly was made up and run in hole. The drill bit hit cement at 2,787 m, followed by cleaning out of a 30 m thick bottom fill to 3,000 m. After cleaning the well, the string was pulled out of hole and followed by run in hole with a cement string for cementing big loss below the casing shoe to 3,000 m. A run in with 8 ½" motor and MWD followed to drill out the cement plug from 2,927 m. At 3,003 m the loss began again and a total loss was experienced at 3,060 m.

Making up a coring drill string followed and the first core run. Once retrieved the core barrel was worn and without any core in the barrel. A steel thermistor holder for temperature logging during coring was missing so a cement job and side tracking had to follow. Again, losses began soon after drilling began with total loss at 3,117 m. POOH for plug cementing the loss zone followed. During a whole month 12 plug cementing operations were repeated altogether down to a depth of 3,185 m. Two failed coring attempts were also done during this time which also included some weather delays. After all this it became clear that the well would not be drilled unless by accepting total loss of circulation from then on to target depth. As cutting cleaning problems were constantly expected the preplanned drilling rate was reduced. During the blind drilling the rig got stuck several times and notably it always occurred right after a polymer pill had been circulated through the bit. Therefore, continuous bleeding of polymer and Guargum mixture (25 l polymer + 25 kg Guargum/hour) to help cleaning the well was started while drilling ahead. That seemed to improve the situation as compared to inserting polymer pills at every single. Fortunately, the rig drilled into an open fracture zone near to ~3,350 m which also helped with the cleaning process, and cooling of the well while drilling. To prevent stuck pipe and cleaning problems the rate of penetration (ROP) was kept below 5 m/h below 3,500 m. Several more openings or feed points were intersected deeper down, but mostly detected by down hole T-logs.

At the beginning of the spot coring operation there were severe difficulties in recovering drill cores and overall only a total of 27.3 meters of cores was retrieved in 13 attempts, or about 63 % recovery of the cored intervals. There were 10 core runs attempted with the IDDP 8 ½" coring tool, and 3 successive core runs with 6" Baker Hughes tool at the bottom of IDDP-2, beneath the 7" liner. Prior to coring with the 6" tools, an 8 m deep 6" pilot hole was drilled with a tri-cone bit from 4,626-4,634 m, firstly to cut the casing shoes and to clean out a bottom fill after setting the casing and conditioning the well. Closer description of the coring and its implication for the lithology and hydrothermal alteration is discuss elsewhere (Weisenberger et al., 2017; Friðleifsson et al., 2017, 2018, Zierenberg et al, 2017, 2020), while a list of the core runs with some core recovery is listed in Figure 2 above.

In Figure 6 below a comparison is shown between the drilling progress and the scheduled estimate. By looking at the figure one can see when loss zone problems begin right below 3,000 m, resulting in one month's gap between scheduled and actual progress, while it was tried to cure the loss zones for better hole cleaning. The coring attempts were only 13 instead of 18 planned due to drilling problems and coring problems and poor core recoveries. The planned depth in the figure was 5,000 m but drilling was stopped earlier after the rig had been stuck for 3 days and several drill pipes came seriously damaged out of hole as can be seen in Figure 7 below.

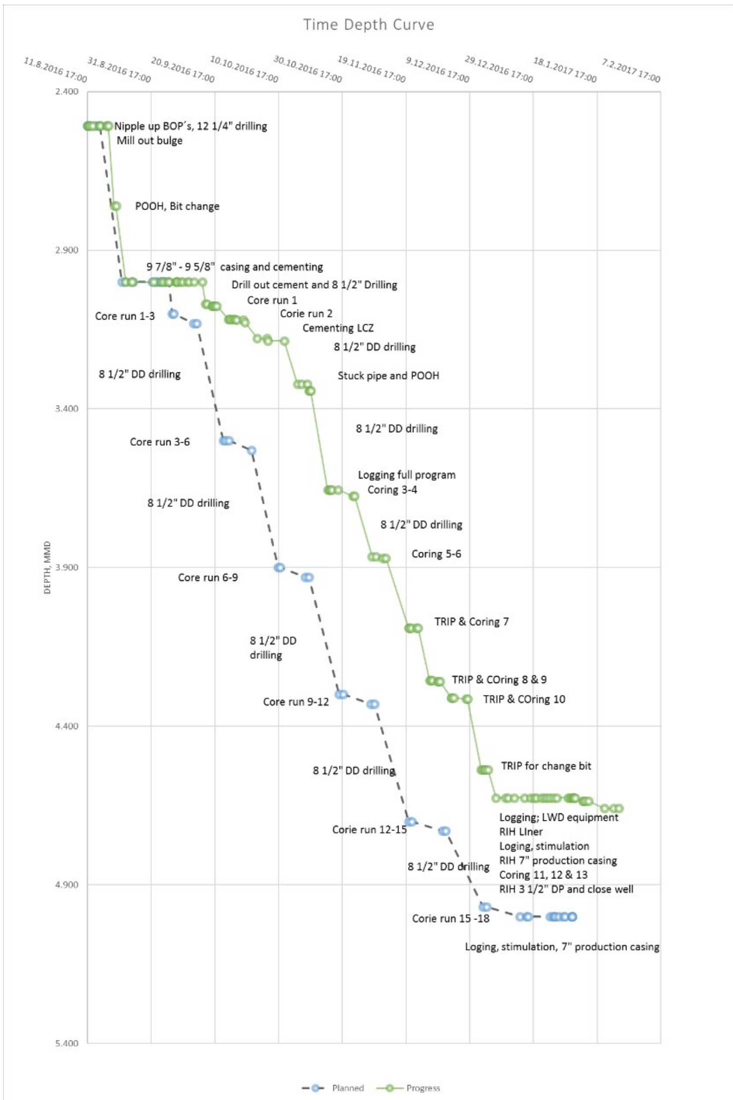

Figure 6. Planned drilling and actual progress of drilling

Figure 7. Damaged drill pipes after having been stuck in a keyhole for 3 days

2.3 Drilling tools used

2.3.1. Conventional tools and bits – downhole motors mostly - including a prototype downhole motor

Table 2 below summarizes relevant BHA runs on IDDP-2. Not all runs are listed in the table since many runs were using same BHA. The reason for most pulling out of hole were for cementing of loss circulation below casing shoe for solving cleaning problem.

Table 2 BHA and bit record

Run #	In (m)	Out (m)	Bit Dia	Bit Type	Bit IA DC	BHA	Drilled (m)	Drilling (h)	Inc (deg)	ROP (m/hr)	WOB (klbs)
1	2500	2523	12,25	VM-R35CG DX	547	Rotary	23	6		3,8	17,7
2	2523	2754	12,25	KM633X	HYB	MIXL Motor	231	32,9	2,4	7	22
3	2754	3000	12,25	VM-44C	627	MIXL Motor	246	34	10,63	7,2	20,9
5	3000	3069	8,50	300C VMG-44CDX2	627	MIXL Motor	69	7	12,92	10,3	14,3
6	3022	3117	8,5	VMG-44C	627	MIXL Motor	95	15	14,33	6,3	7,7
C1	3069	3074	8,5	Rok-Max		Rotary	0,0	7,1		0,8	0,0
7	3117	3119	8,5	MX-44G	617	Rotary	2	72,5		0	8,8
8	3119	3178	8,5	MXL-44C	627	Rotary	59	9		6,6	22
C2	3178	3179	8,5	Rok-Max		Rotary	0,0	2,0		0,7	0
10	3185	3321	8,5	300C VMG-44CDX2	627	Rotary	136	38,5		3,5	22
11	3321	3648	8,5	300C VMG-44CDX2	627	Rotary	327	103		3,2	11
C3	3648	3649	8,5	Rok-Max		Rotary	0,5	5		0,2	
C4	3649	3650	8,5	Rok-Max		Rotary	0,0	10		0,2	
12	3650	3865	8,5	VMG-44C	627	M2M Moto	215	79,4	29,5	2,7	9,9
C5	3865	3870	8,5	Rok-Max		Rotary	3,9	8,5			
C6	3870	3870	8,5	Rok-Max		Rotary	0,15	2,5			
13	3869	4090	8,5	VMG-44C	627	M2M Moto	221	89,9	27,4	2,5	16,5
C7	4090	4090	9	Rok-Max		Rotary	0,13				
14	4091	4254	8,5	VMG-44C	627	MIXL Motor	163	32,7	28,5	4,98	15
C8	4254	4255	8,5	Rok-Max		Rotary	0,28				
15	4255	4309	8,5	VMG-44C	627	Rotary	55	27,5		2	4,4
C9	4309	4310	8,5	Rok-Max		Rotary	0,00				
C10	4310	4311	8,5	Rok-Max		Rotary	0,22				
16	4311	4537	8,5	VMG-44C	627	Rotary	226	63,5		3,6	11
17	4537	4626	8,5	VMG-44C	627	Rotary	89	48		1,9	6,6
19	4626	4634	6	STX-20	517	Rotary	8	6		1,33	5,5
C11	4634	4642,5	6	BHC309	M443	Coring	8,5				
C12	4642,5	4652	6	BHC309	M443	Coring	9,5				
C13	4652	4659	6	BHC309	M443	Coring	7				

As can be seen in the table there are 5 difference BHAs used for the drilling of the well, that is conventional rotary assembly, conventional motor assembly, assembly for high temperature motor, rotary assembly for 8 ½" coring and rotary assembly for 6" coring. When drilling geothermal wells in Iceland most of the production section is drilled with no returns. In drilling the IDDP-2 we had numerous openings on the way down that did help with cooling the well and the tools. Best way to measure the temperature while drilling is the MWD tools where the sensors are more than 4 m above the motors and more than 14 m above the drill bit. We can than assumed the tools below the sensors have seen higher temperature than is read form the MWD tool. The maximum temperature reported on the MWD tool was 127°C while drilling between 3,022 m to 3,177m.

The original well was deepened from 2,500m to 3,000m with 12.25" roller cone and hybrid bits on rotary and conventional motor BHAs, see table 2.

The 8.5" section used rotary, motor and coring BHA runs, see table 2. Both MIXL motors and the prototype 300**°C** M2M motor was used and the bit used were Roller cone bit, Geothermal roller cone Bit and 300°C roller cone bit.

- <u>Roller cone bit</u>: metal face seal technology rated for 177°C

- Geothermal roller cone bit: metal face seal technology rated for 288°C
- 300°C roller cone bit: full metal seals/bearings/compensators technology, 300°C grease formulation

Roller cone bit   Geothermal roller cone Bit   300°C roller cone bit

Figure 8. Three bit-types used in the 8.5" section of IDDP-2

2.3.2. Coring tools

An IDDP coring tool, specially design and build in 2005 (Skinner et al., 2009 A, B), was used for the coring operation to begin with. The special feature of the IDDP coring tool is its allowance for much greater water passage for cooling extremely hot rock formation, or up to 40 l/s which is an order of magnitude higher flow rate than that used for conventional spot coring tools. Another characteristic feature of the IDDP tool is the relatively soft coring bits, designed for single use only. Since first testing the coring bits have been modified slightly (Figure 9 A). The tool was first tested in Reykjanes well RN-17B at 2,800 m depth in an 8 ½" hole – with perfect result – i.e. both in running it into hole (with minor difficulty) and good core recovery with very interesting rocks (Friðleifsson and Richter 2010). The tool was later used in well RN-30, also at Reykjanes, and in both cases in directionally drilled holes. The three successive spot cores in RN-30 gave very satisfying result, but in this case the coring tools were run in hole through a 9 5/8" perforated liner, giving good support to the coring tool and no obstructions. In other IDDP coring attempts (Krafla (IDDP-1), Þeistareykir and Svartsengi) we did not get any cores and the performance in all cases were not satisfactory, while for different reasons. We had been using three types of drill rigs, and the well conditions were unstable in the earlier two attempts, and an inclined 8 ½" hole in the third case.

Unfortunately, the coring operations in IDDP-2 were quite difficult and unsatisfactory from the very beginning. We did not get any core in the first two runs, then 0.5 m in the third run. In attempt to overcome some of the problems the core barrel was shortened from 10 m to 5 m, cutting off all the stabilizers on the BHA, and using only one stabilizer above a heavy drill collar and the BHA. After that modification (in core run 4) the situation improved, and 3.85 m of core was retrieved in a 5 m barrel. Possible reasons for the poor performance of the 8 ½" coring assembly were (a) the inclination of the hole, which increased with increasing depth, (b) possible dog-legs in the hole, (c) the relatively soft drill bits banging against the well wall on running in, (d) the diameter of the coring tool itself and reamers, which exceeded by an inch the diameter of the heavy drill collars in rotary drilling. Accordingly, the coring bottom-hole-assembly (BHA) was stiffer that the drill collar BHA alone while rotary drilling. Three stabilizers were put in the BHA above the coring tool. In some case the 8 ½" tri-cone bit may have been slightly under size, adding to the problems. In some case the hole had also to be reamed for considerable lengths before getting to the bottom; in other case fill in the hole may have hindered good performance for coring. However, after our modification the situation did not improve sufficiently to satisfy our need for drill cores. Nevertheless, recovering tens of centimeters of core made a huge difference scientifically, compared to having no rock samples at all.

Overall only a total of 27.3 meters of core was retrieved in 13 coring attempts, thereof 10 core runs with the IDDP 8 ½" coring tool and 3 successive core runs with 6" Baker Hughes tool at the bottom of IDDP-2, beneath and after having inserted a 7" liner. Prior to coring with the 6" tools, an 8 m deep 6" pilot hole had been drilled with tri-cone bit from 4626-4634 m, to clean out the bottom fill after casing and to condition the well. The Baker Hughes coring operation was exceedingly smooth, and to demonstrate that a comparison in torque in the 13 core runs is compared in Figure 10 B. The last 3 core were also drilled in the hottest rock in the hole, where heat is somewhere between 500-600°C (Sigurðsson, 2020; Zierenberg et al., 2020) and the rocks accordingly close to ductility. The one and the same 6" core bit (Figure 9 B) was used in all last three core runs, and the core bit hardly worn after the coring. The immediate lesson learned is that in the future we should probably use slimmer coring assembly in inclined wells, such as drilling 6" in an 8 ½" hole, or 8 ½" in a 12 ¼" hole, etc.

Core bit	Core bit size	Description	Used in core run	Image
1st generation (Rok-Max Drilling Tools Ltd.)	8½"	These were the first bits produced. Impregnated diamond cast matrix and has ½" wide junk flush slots.	5, 6, 7, 8, 10	
3rd generation (Rok-Max Drilling Tools Ltd.)	8½"	Same matrix as previous bits, internal flush with semi-round profile. ½" width junk flush slots	1, 2	
4th generation (Rok-Max Drilling Tools Ltd.)	8½"	High density T.C. cast matrix with 5 mm and 10 mm Geocube type cutters, face discharge (9 x ½"), internal discharge	3, 4, 9	
BHC 309 C (Baker Hughes)	6"	The core bit uses a short parabolic profile to core at optimum penetration rates and reduce likelihood of jamming.	11, 12, 13	

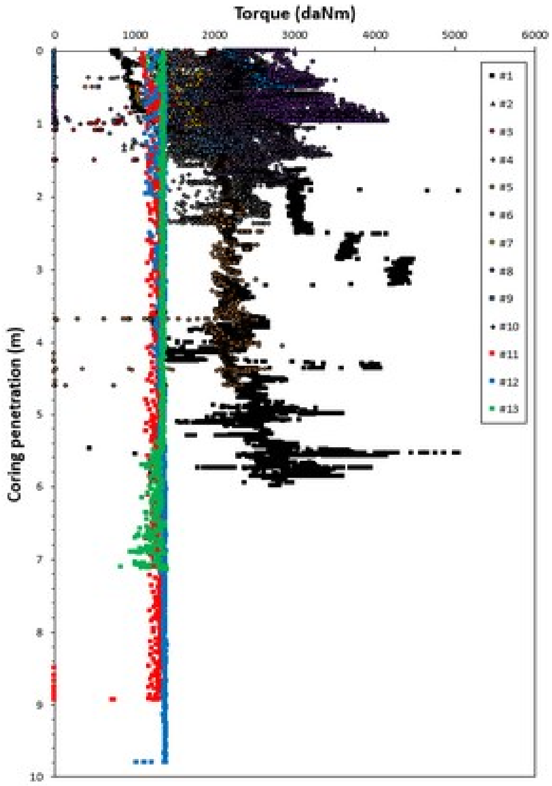

Figure 9. A) Three generations of core bits from the IDDP coring tool, and one 6" PCD spot coring bit from Baker Hughes B) Comparison of torque in the 13 spot coring attempts performed in IDDP-2 well (figures in Weisenberger et al., 2017). Core runs 11, 12 1nd 13 ae colored red, green and blue.

2.4 Physical logs

During the planning stage of deepening well RN-15 it was expected that circulation losses would be small below 3,000 m depth. Known temperature at 2,500 m depth in the well was ~285°C and the formation temperature was rather expected to increase along a gradient with depth and likely to approach the boiling point temperature (BPC) for seawater, which would make the extrapolated temperature over 410°C at 5,000 m depth. Therefore, it was expected that the well would warm-up rather quickly below 3,000 m so use of regular wireline logging tools would not be feasible. For obtaining logs from the deeper part of the well a search for logging while tripping (LWT) or logging while drilling (LWD) tools was conducted. However, as loss zones were encountered below 3,000 m during the deepening an attempt was made to obtain logs with the conventional geophysical logging tools available at ISOR in Iceland, rated for temperatures up to about 150°C.

A regular logging suit was measured in the well before cementing the production casing. The wireline suit consisted of normal resistivity, neutron and natural gamma to 2,775 m, and XY-caliper to 2,870 m. The tools stopped at sills or washouts in the well and would not go deeper. Also, an acoustic televiewer imaging was obtained for selected intervals between 860-2,305 m. When the well was 3,648 m deep an attempt was made to log the well again with the available wireline tools. Normal resistivity, neutron and natural gamma, and sonic log was obtained from casing depth to 3,440 m. Televiewer log was attempted but had poor quality due to bad centralization. As earlier the tools stopped at some sills or washouts in the well that limited the depth coverage of the logs.

At end of drilling when the depth was 4,626 m a special logging run with LWD tools from Weatherford was carried out. Such tools had not been used earlier in Iceland. The logging suit consisted of natural gamma, temperature, pressure (HEL/BAP), and multi frequency resistivity (MFR) from casing to 4,615 m. Micro-resistivity imaging (SMI) to 4,490 m (good quality) and acoustic velocity (SST) to 3,045 m. The acoustic tool and the imaging tool were damaged possibly due to relatively stiff logging string and high rotation hence the logs below the indicated depths are not reliable. With circulation during insert the temperature on the tools could be kept below 65°C during the log-run though the tools were logging were formation temperature was rising downwards to around 500°C or more near bottom.

Additionally, to the above logs, several temperature and pressure profiles were measured (exemplified in Figure 5 above), CBL, gyros, MWD, injectivity and three spinner logs (3,158 m, 3,646 m, 4,420 m). In general, the logs give valuable information on the formation physical properties, especially as no drill cuttings were obtained.

3. LESSON LEARNED

There are several items that can be addressed here as a lesson learned from the drilling of the deepest geothermal well in Iceland.

Firstly, directional drilling should be avoided in drilling very deep high temperature geothermal wells as it increases potential for various problems that increase with depth. This, however, was well known before we began drilling the IDDP-2 well and were discussing and designing IDDP wells in general (e.g. Thorhallsson et al., 2014; Friðleifsson (ed.), 2003). In the IDDP-2 case directional drilling was needed to take the well path towards the up-flow zone of the Reykjanes reservoir and to find as high temperature as possible, preferably supercritical conditions. Due to total circulation losses and potential of getting the drill string stuck the directional tools (MWD) were in and out as part of the bottom hole assembly (BHA). As a result of that the inclination of the well went out of control. Later that influenced creation of keyholes hindering normal tripping of the string and few times keeping the string stuck in the hole. Finally, a decision not to drill the well deeper was caused by the rig getting stuck in a keyhole for almost three days. Once the drill string was on surface severe damages were observer on several drill pipes indicating that the string could have easily been twisted apart.

Next to mention, is the mitigation we used for cleaning the well by bleeding HT polymer and Guargum continuously while drilling helped greatly in keeping the well clean and the standpipe pressure much lower than when drilling with water alone.

Then we can look at the coring problems that we had in the 8 ½" section. Coring with 8 ½" core bit and 7 1/8" core barrels clearly called for problems since the core barrel was far too stiff for smooth run into 8 ½" inclined bore hole. We should probably use 6" core bits on 4 ½ core barrel in 8 ½" inclined well for coring, and then ream out the hole to 8 ½" before continue drilling again. It can also be mention that cooling of the well while drilling was not a problem, as could be seen from the MWD drilling tool below 4,000 m, where temperature never exceeded 50-60°C.

The 7" sacrificial casing that was designed for use in top of the well, partly to enforce the pressure barrier, turned out to cause problem afterwards once a need arose to enter the well with larger diameter milling tools for casing repair. This can also cause future problems for any device used in the well, such as any logging tools or fluid samplers or other use.

Use of circulation blockers such as the AltaVert blocker used during the deep stimulation, blocked cold water flow on the annulus completely for a while and may have caused the casing to heat up which could result in casing damages. So, an additional risk factor is imposed by such stimulation effort. Using several km long drill string for stimulation with fresh water without inhibitors to prevent oxidation and corrosion is also questionable. The drill string was severely corroded once retrieved and the perforated liner close to the bottom well undoubtedly too. Accordingly, mitigation action is recommended.

Experience is lacking when it comes to drilling into extremely hot rocks like in IDDP-2, 400-600°C hot. Therefore, one needs to expect that the tolerance limits of conventional drilling and logging tools could be surpassed if something happens like a stuck or twisted drill string, or a loss of circulation through the drill bit. In the IDDP-2 well continuous total loss of circulation fluid into the rock formation was somewhat unexpected, but surely helped to keep the casings and wellbore chilled during drilling and enabled the feeding of cold water on the annulus throughout the drilling operation. In using predrilling model calculation, however, to predict the temperature condition while drilling for choosing drilling tools, and to predict the heat in the well before cementing the production casings, a different situation was assumed, or a condition without circulation loss. Therefore, a predrilling decision was made to use a retarder in the cement slurry which proved not to be necessary. It did cause much longer settling time than was necessary. Cement mixtures and additives should be decided upon on site once the well condition is known. In cementing operation, a so called "free fall" zone is created mainly due to density difference between wellbore fluid at beginning of cement job and the cement slurry. In this free fall zone, an under pressure is created which needs to be considered especially for reverse circulation cementing (RCC). If the length of the free fall zone extends over intervals in the well where active loss zones are located, then fluid from those zones can be sucked in to the annulus changing the water content of the slurry and possibly even create water pocket behind the casing. In designing RCC jobs one of the objects is to minimize the likelihood of such contamination. This is done by playing with the slurry pumping rate.

For directional well it is important to be able to control the azimuth and inclination while drilling. That in turn requires that the hole conditions to be manageable so needed measurements can be taken without increased risk to well or equipment. That was not always the case. Total loss of circulation was persistent during the drilling operation that sometimes affected the well cleaning. The well also intersected some unstable formations that affected the torque of the drill string and increased the potential for the drill string to become stuck. To minimize financial risk the MWD tool was taken out from the bottom hole assembly (BHA) while drilling through some of these trouble zones. However, that reduced the control over the azimuth and inclination of the well which later led to formation of keyholes with associated problems.

Basically, no cuttings were received on surface during the drilling operation due to total loss of circulation throughout the operation. About 60 m^3 of cuttings were generated by the drilling and basically all of it was lost to the fractures and loss zones that the well intersected. Repeated circulation loss occurred in the 200 m interval below the anchor casing despite attempts to plug them off with cement plugs, which indicates fairly open loss zones. Further, measurements indicated at least 3-4 loss zones deeper and several fractures that were not necessarily active loss zones. The zone around 3350 m appeared from logs to be about 20 m high near vertical fracture. Assuming fracture aperture around 1 cm and that the fracture extends at least 20 m into the formation then the fracture around 3350 m could have accepted over 4 m^3 of cuttings. Assuming further that other fractures or opening between formation layers resemble penny shape then 4-5 fracture could take the rest of the cuttings. This compares reasonably well with observation and could indicate relatively large fracture space in the formations.

ACKNOWLEDGEMENT

Drilling of IDDP-2 was funded by HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, Orkustofnun in Iceland, and Statoil (now Equinor). Additional funding was received from the EU H2020 programme to DEEPEGS, grant no. 690771. Funds for IDDP spot coring and science studies from ICDP and NSF (grant no. 05076725) in 2005. All this is greatly appreciated. The drilling contractor was the Iceland Drilling Company (IDC) and we thank their drilling team and managers for good job done and good cooperation throughout the drilling operation. Similarly, we acknowledge the ISOR team, the members of the IDDP science team, domestic and international, for teamwork and discussions throughout the years on this challenging IDDP/DEEPEGS project.

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