IDDP – APPROACHING THE SUPERCRITICAL

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ABSTRACT

The Iceland Deep Drilling Project (IDDP) is investigating the economic feasibility of producing electricity from supercritical geothermal reservoirs. Modelling suggests that producing superheated steam from a supercritical reservoir could potentially increase power output of geothermal wells by an order of magnitude. To test this concept the consortium intends to drill 4-5 km deep wells in three different high–temperature geothermal fields in Iceland, Krafla, Hengill and Reykjanes. The drilling of the IDDP-1 took place at Krafla in 2009, but had to be terminated at 2.1 km depth when the borehole drilled into >900°C molten rhyolitic magma. The borehole was completed as a production well and proved to be highly productive, estimated to be capable of generating 25-35 MWe from dry superheated steam, produced from a contact zone above the magma intrusion. With a wellhead flowing temperature of 450°C and enthalpy around 3200 kJ/kg, it holds claim to be the hottest producing geothermal well in the world. In July 2012 flow testing to optimize utilization had to be temporarily terminated for repair of the flowline valves after more than 2 years of testing.

Plans are underway to drill a new 4-5 km deep well at the Reykjanes field in 2014-2015. An international IDDP-ICDP Workshop was conducted in Iceland, September 2012, in order to discuss and evaluate the IDDP-1 situation and plan ahead for IDDP-2. No issues were identified that should rule out attempting the drilling, sampling and testing of the proposed IDDP-2 well. The consensus of the workshop was that the drilling of such a hot, deep well, and producing from potentially hostile, supercritical or superheated fluids, although technically very challenging, is possible but requires careful contingency planning.

1. INTRODUCTION

The IDDP was established in the year 2000 by a consortium of three Icelandic energy companies, Hitaveita Suðurnesja (now HS Orka hf) (HS), Landsvirkjun (LV) and Orkuveita Reykjavíkur (OR), and Orkustofnun (OS) (the National Energy Authority of Iceland). The same year the basis for the IDDP concept of drilling for geothermal resources at supercritical condition (374°C and 222 bars for pure water) was further explained at the World Geothermal Congress (WGC) 2000 in Japan (Friðleifsson and Albertsson, 2000). Supercritical water has much higher enthalpy and lower viscosity than a two phase mixture of steam and water at subcritical temperatures and pressures (Dunn and Hardee, 1981; Hashida, et al. 2001; Fournier 1999). Our modelling indicates that a well producing supercritical water could have an order of magnitude higher power output than that from a conventional high-temperature geothermal well, given the same volumetric flowrate (Albertsson et al., 2003; Friðleifsson and Elders, 2005). However, reaching supercritical conditions is expected to require deep drilling (>3.5 km), even in areas of high heat flow. From the outset, the IDDP consortium welcomed the inclusion of basic scientific studies in the IDDP (Friðleifsson and Albertsson, 2000; Elders et al., 2001; Friðleifsson and Elders, 2005). The guiding principle was that the incremental costs of drilling and sampling for the science program, and their subsequent study, should be met by the scientific community. In 2005, HS made available a well of opportunity to IDDP for deepening, i.e. well RN-17 at Reykjanes, but unfortunately that well was lost during a flow test later that year, before IDDP could approach the well for deepening. In June 2006, a decision was made to move the IDDP operations to Krafla in NE-Iceland (Fig. 1). Funding for deepening that well had already been secured by the Icelandic consortium and funds for scientific coring was awarded from both the International Scientific Continental Drilling Program (ICDP) and the United States National Science Foundation (NSF) in 2005.

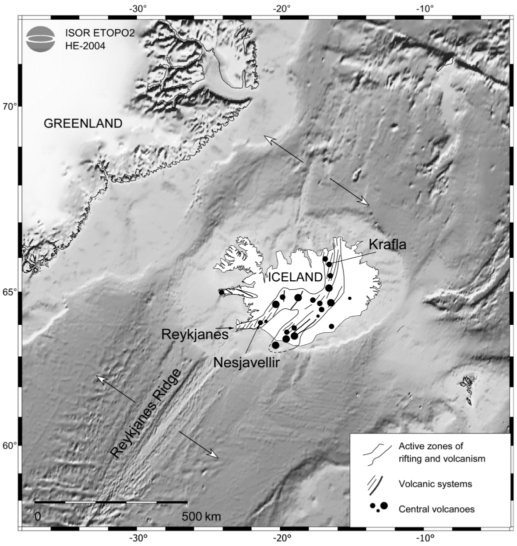

Figure 1: Map of Iceland and the North Atlantic ocean floor, showing the active zones of rifting and volcanism through Iceland, that are the landward extensions of the Mid-Atlantic Ridge, Locations of the three high-temperature geothermal systems of Krafla, Hengill (Nesjavellir) and Reykjanes, selected as sites for deep drilling by the IDDP.

In 2007, Alcoa Inc. (Alcoa) joined the IDDP consortium followed by Statoil in 2008. In 2007 the three Icelandic power companies announced their commitment to drill at their own cost a 3.5-4.0 km deep well in each of the three named geothermal fields. These wells were to be designed to suit deepening to 4.5-5.0 km depth. The deepening of one of these wells as a joint IDDP project would then be funded by the energy consortium, with additional funds from ICDP and NSF. IDDP continues to welcome international participation to the IDDP program (Friðleifsson et al., 2010).

2. DRILLING AND TESTING OF IDDP-1

The first well in the program, IDDP-1, was drilled in 2008-2009 in the Krafla volcano in NE-Iceland. The plan was to rotary drill the IDDP-1 down to 3.5 km depth and cement in the steel production casings, funded by Landsvirkjun (LV). Then, the IDDP consortium would fund the deepening of the well to 4.5 km into the supercritical zone, and the ICDP and NSF fund a number of spot cores for scientific purposes. However, the drilling of the IDDP-1 well had to be stopped at 2.1 km depth, as the drilling unexpectedly intersected hot (900°C) rhyolitic magma (Elders and Friðleifsson, 2010; Elders et al., 2011; Hólmgeirsson et al., 2010). IDDP decided to add a 9 5/8 inches sacrificial casing, cemented to 1950 m depth, with a slotted liner to 2078 m depth. This enabled safe flow testing of the lowermost part of the well just above the magma interface. The design of the well and wellhead was believed to be sufficiently robust for the expected flow conditions.

Extensive studies of the rhyolitic magma indicated the estimated temperature of the magma to have been 900°C, with a volatile saturation pressure of about 40 MPa, a value between hydrostatic and lithostatic. The very low value of δD in the rhyolitic glass (-121 ± 2 ‰) is remarkably similar to that of hydrothermal epidotes from Krafla geothermal wells and could not be produced from hydration by local geothermal waters nor by mantle-derived waters, and instead the source of its hydrogen is apparently derived entirely from hydrothermal alteration minerals. Thus this rhyolite magma formed in a basaltic volcano by partial melting of hydrothermally altered basalts.

Figure 2:Dark colour at the beginning of each flow test, due to casing corrosion, lasts for about 5 minutes, then the steam turns transparent and superheated as in figure 3.

The IDDP-1 well has been intermittently flow tested beginning in May 2010. Several modifications needed to be conducted on the wellhead and flowline, and additional testing equipment proved necessary to accommodate the powerful well (Ingason et al. 2013 (in prep.) and Hauksson et al. 2013 (in prep.)). Depending on turbine type, the well appears to be capable of producing between 25-35 MWe, whilst free chlorine gas and sulphur in the superheated team is managed by wet scrubbing. Pilot tests related to direct use and heat exchange system, and experiments concerning corrosion tests etc. have been undertaken and reported (Ingason, op.cit; Hauksson op.cit; Ármannsson et al., 2013 (in prep.)). After the initial flow tests, the well produced 10-12 kg/sec of superheated steam at 450°C, 140 bar pressure for more than a year, with fluid enthalpy believed to approach 3200 KJ/kg, under restricted flow condition. The well had to be closed in late July 2012, in order to repair the flowline valves. Unexpectedly, both master valves malfunctioned at that time, and the well had to be cooled by cold water, which resulted in damage to the sacrificial casing. At the moment it is not clear if or when the IDDP-1 well will be allowed to re-heat and produce again.

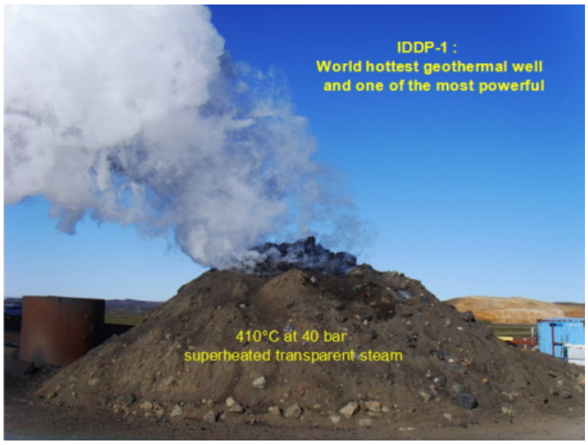

Figure 3: After about 5-10 minutes of flow through fully opened well, the dark steam turns transparent and superheated, and maintains so as long as the well is kept open. Video clips of the flow test are available at www.iddp.is.

Although the IDDP-1 did not reach depths at which supercritical pressures exist, it was a success both scientifically and from an engineering standpoint. A special issue of the Journal Geothermics with 15 papers on the IDDP-1 (and IDDP-2) will be published shortly. Perhaps in the future, such accessible magmas will be used as sources of very high enthalpy geothermal energy in Iceland, and elsewhere, wherever suitable young volcanic rocks occur.

One speculation, briefly discussed at an IDDP-ICDP workshop held in September 2012, was a suggestion that flow testing of the IDDP-1 well might have created an Engineered Geothermal Systems above the magma chamber. During and after drilling and casing of the well, total circulation loss of the drilling fluid was experienced. Hydro-fracturing of hot contact rocks, just above the rhyolitic magma, may have been the case. The well was extensively cooled for several months, and thereafter heated slowly. Once allowed to flow, however, the pressure drop in the well should have been felt by the overlying conventional two-phase geothermal system. That could have resulted in a downwards fluid flow towards the heat source and up the wellbore as superheated steam. Speculative ideas like this can be tested, by applying suitable tracers, but if is the case, the IDDP team may have unintentionally created the world's first magmatic EGS system.

2. THE IDDP-ICDP WORKSHOP 2012

A workshop on the Iceland Deep Drilling Project (IDDP) was held in Iceland at the Eldborg Conference Centre, at Svartsengi, SW Iceland, from the 3rd to the 5th of September 2012. The aims of the conveners of the workshop were: (1) to review the lessons learned from the IDDP-1; (2) to develop the criteria for optimizing the drilling of the IDDP-2; (3) to review the specifics of the site selection; (4) to define the drilling target better; (5) to broaden the scope of international participation and disciplinary range of the science program; (6) to coordinate the engineering and science programs; (7) to develop and coordinate strategies for funding both IDDP-2 engineering and science activities; (8) to invite broader international and disciplinary participation, and (9) to prepare and distribute a report on the results of the workshop that documents its findings and recommendations and publicizes the engineering, technical and scientific opportunities that the IDDP-2 offers.

The economic motivation behind the Iceland Deep Drilling Project (IDDP) is that deeper geothermal wells that penetrate higher enthalpy resources capable of producing supercritical fluid, or even high-pressure superheated steam, have the potential to greatly enhance the power output of geothermal fields, without enlarging their size and environmental footprints. The workshop was funded by the International Continental Drilling Program and by the Deep Vision, the steering committee of the IDDP. Workshop participants reviewed the lessons learned from the first IDDP-1 exploratory borehole, in 2009, at the Krafla Volcano in NE Iceland, as discussed above. Deep Vision invited participation by the international community in the ongoing IDDP to maximize the scientific and technical impact of the project. As the geothermal fluid at Reykjanes is modified seawater, this IDDP-2 will provide the first opportunity worldwide to directly investigate the root zone of a magma-hydrothermal system that is a likely corollary to those beneath the black smokers on the world-encircling mid-ocean rift systems. Zones of intense water-rock reaction along rift systems are exceedingly important for the practical goals of the IDDP. It is there, that fluids are heated and interact chemically with their host rocks, where most of the Earth's heat transport and chemical alteration take place, and where high enthalpy superheated steam or supercritical water should be most easily accessible for power production and research.

Ninety-four engineers and scientists attended the workshop; about two-thirds were from Iceland and the rest from Canada, France, Germany, Japan, Italy, Netherlands, New Zealand, Norway, Switzerland, UK and USA. Several presentations were also made concerning similar ambitious projects in Japan and New Zealand that are concerned with drilling into deep, high-enthalpy, geothermal systems in those countries. Breakout sessions at the workshop allowed smaller groups to discuss the topics of drilling, hydrology, geosciences and fluid handling, and to prioritize activities that should be carried out before, during and after IDDP-2 drilling, together with other activities that are complementary to the goals of the IDDP.

No issues were identified that should rule out attempting the drilling, sampling and testing of the proposed IDDP-2 well at Reykjanes. The consensus of the workshop was that the drilling of such a hot, deep well, and producing from it, potentially hostile, supercritical or superheated fluids, although technically very challenging, are possible but require careful contingency planning. Another challenge will be building on the enthusiasm expressed at the workshop by participants of different nationalities, different areas of expertise, and different institutional affiliations. We anticipate that the outcome of the IDDP-ICDP workshop will bear much fruitful technical and scientific collaboration between the deep geothermal exploration programs, such as in New Zealand, Japan, Italy, USA and elsewhere, where similar geothermal conditions and issues need be understood. The result and recommendation of the IDDP-ICDP workshop is described at length in the IDDP SAGA Report 2012 (www.iddp.is).

3. DRILLING OF IDDP-2

Planning for the second deep well, IDDP-2, to be drilled in the Reykjanes Geothermal Field in SW Iceland is now underway. Once more the plan is that the field operator (in this circumstance HS Orka hf.) will fund and drill the well to ~3.5 km, and that the IDDP consortium will then fund deepening and testing of the deepened well. Once again the IDDP is inviting international scientific participation with the international science team again being responsible for obtaining funds for scientific sampling, data collection, and study, both onsite and in the laboratory.

HS Orka is now in the final stages of negotiating for a major expansion of the geothermal power plant at Reykjanes. Some 20 production or injection wells exist in the field, so much is known about the upper 2.5 km of the geothermal system. The proposed expansion will require drilling of at least six new production and injection wells in the Reykjanes field, and the last one in that series could be the IDDP-2. This timetable will allow the planning and drilling the IDDP-2 to benefit from the new information and the experience gained from drilling the new wells.

Figure 4: The photo shows the Reykjanes well field and the 100 MW$_e$ power plant in the background. A tentative site for well IDDP-2 is in the area to the right of the steam separation house in the middle of the photo. That siting, as well as the drillhole design, is now being re-evaluated.

Due to the drilling problems, the cost of drilling of the IDDP-1 at Krafla was very high. The total cost of drilling and testing probably approached about 20 million USD. The HS Orka team is currently re-evaluating the drilling program and cost estimates for the IDDP-2 well at Reykjanes in order to optimize the future drilling and testing, while significantly lowering costs. One option would be to scale down the drilling program by drilling and casing a smaller diameter well than the IDDP-1, if this can be done without jeopardizing safety or the economic goal of exploring and producing the Reykjanes geothermal system from 3-5 km depth. This re-evaluation is expected to be completed in 2013. Nevertheless, it is quite clear that any expenditure of funds by the international science program will be highly leveraged by the very large contribution by the engineering program of HS Orka and the IDDP consortium. It is their funding that will create the opportunity for the science team to participate and the scientists will also benefit from the extensive practical experience and technical capability of the Icelandic geothermal industry.

4. CONCLUSION

The most important outcome from the IDDP effort this far, is that none of the wide ranging discussions of drilling, fluid handling, and geoscience, at the IDDP - ICDP Workshop 2012, identified "critical project issues" that should cause abandonment of the project. Producing much higher enthalpy geothermal fluids from the deeper, hotter, potentially supercritical zone, beneath the producing geothermal reservoirs in Iceland remains an attractive target. Nevertheless, drilling and testing these exploratory boreholes will be technically challenging and expensive. The experience gained from the IDDP-1 well reinforced the truism that drilling leads to surprises, requiring careful contingency planning. Better definition of the conditions in the target zone is a basic requirement for such planning. The discussions at the workshop and the activities suggested before drilling will reduce risk, and put plans for the IDDP-2 on a more confident footing.

ACKNOWLEDGEMENTS

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