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The Iceland Deep Drilling Project – A Search for Unconventional (Supercritical) Geothermal Resources

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ABSTRACT

The Iceland Deep Drilling Project (IDDP) is a long-term program by an Icelandic energy consortium to improve the economics of geothermal energy by producing supercritical hydrous fluids. A two year-long feasibility study was completed in June 2003 and in November of the same year a decision was reached to proceed, and to seek international funding for deep drilling from both the energy industry and from science foundations. Drilling of the first deep drillhole will begin early in 2005 in the Reykjanes high-temperature geothermal field, at a strategic site where the Mid-Atlantic Ridge emerges from the ocean. A 2.7 km deep well will be drilled, completed by a 12 ¼" rotary bit and left barefoot for flow testing. Funding for casing of the well, in summer 2006, and then rotary drilling from 2.7 km to 4.0 km and subsequent flow testing, is being sought from the industry and international funding agencies. We plan to take several spot cores in this depth interval. After evaluation of the technical and scientific results from the 4.0 km deep well, we plan to deepen the well to 5 km by core drilling into a supercritical geothermal reservoir and carry out a third flow test from that depth.

The primary objective of IDDP is to find 450-600°C supercritical geothermal fluids at drillable depths, to study their physical and chemical nature and the feasibility and economics of using them as an energy source. Although drilling such deep wells will be expensive, modeling indicates that the power outputs from supercritical wells could be enhanced by a factor of 10 relative to the power production usual from high-temperature geothermal wells. This is because supercritical fluids have higher enthalpy than steam produced from two-phase systems and large changes in physical properties near the critical point can lead to extremely high flow rates. If this approach using such unconventional geothermal resources is an economic success the same approach could be applied in other high-temperature volcanic geothermal systems elsewhere, as an important step in enhancing the geothermal industry worldwide. The IDDP could serve as an ideal R&D platform for both a European and an international programme on sustainable energy from unconventional geothermal resources. This programme could integrate the generation of electric power, production of a clean energy carrier like hydrogen, possible production of chemicals in an environmentally sound way, and eco-tourism as part of the "Geopark" concept.

1. INTRODUCTION

Over the next several years the Iceland Deep Drilling Project, IDDP, expects to drill and test a series of boreholes that will penetrate supercritical zones believed to be present beneath three currently exploited geothermal systems in Iceland, at Krafla, Nesjavellir and Reykjanes. This requires drilling to depths greater than 4 to 5 km, in order to produce hydrothermal fluids at temperatures of 450 to 600°C.

Deep Vision is an Icelandic energy consortium (Hitaveita Sudurnesja Ltd., Landsvirkjun, Orkuveita Reykjavikur and Orkustofnun) that began the IDDP in 2000. The principal aim is to enhance the economics of high temperature geothermal resources. A two-year feasibility study was completed in 2003, addressing basic questions such as: Can 4-5 km deep and 450-600°C hot wells be drilled safely? Can they produce fluids? What will be the advantages and disadvantages and the overall economics? Where should the first IDDP well be drilled? The feasibility report is divided into three parts. Part 1 deals with geosciences and site selection (Fridleifsson et al., 2003a), Part 2 on drilling technique (Thorhallsson et al., 2003a), and Part 3 on fluid handling and evaluation (Albertsson et al., 2003a).

From the outset Deep Vision has been receptive to including scientific studies in the IDDP (Fridleifsson and Albertsson, 2000). An international advisory group, SAGA, that has assisted Deep Vision with science and engineering planning of the IDDP, was established in 2001, with financial support from the International Continental Scientific Drilling Program (ICDP). The financial support was used to organize and discuss in detail drilling and scientific issues linked to IDDP. An IDDP/ICDP start-up meeting was held in Reykjavík in June 2001. This was followed by a workshop on drilling technique in March 2002, and a science workshop in October 2002. Altogether some 160 participants from 12 nations participated in the workshops. The essence of these workshops and recommendations to IDDP are described in SAGA reports 1, 2 and 3, respectively, all of which are available on the IDDP website (http://www.os.is/iddp/) and appended to the IDDP Feasibility Report (op.cit.). The IDDP/ICDP workshops and SAGA influenced the feasibility report considerably, and focused many aspects of its approach. A summary of the IDDP feasibility report and the international workshops was published in the proceedings of the International Geothermal Conference 2003 (IGC2003) in Reykjavik (Albertsson et al. 2003b, Elders et al. 2003, Fridleifsson et al. 2003b,c, and Thorhallsson et al. 2003b) and the Transactions of the Geothermal Resources Council meeting in 2003 (Fridleifsson and Elders, 2003). Two additional papers on this subject have been submitted to a special issue of the Geothermics (Fridleifsson and Elders, 2004; Thorhallsson et al. 2004).

Among the chief findings of the feasibility report were:

1) Each of the three target geothermal fields (Krafla, Nesjavellir and Reykjanes, Figure 1) has excellent potential drill sites to reach supercritical conditions.

2) Wells producing from reservoir with supercritical fluids could have power output per well, increased by an order of magnitude, relative to conventional geothermal wells.

3) An IDDP well to 5 km depth can be drilled using available technology.

4) 400-600°C steam can be dealt with and would be much more valuable than lower temperature steam.

5) The fluid composition will not be known until after drilling.

6) An IDDP production well 5 km deep would cost 8-9 million USD.

7) A full scale exploratory IDDP well, with extensive coring required by the science program would cost 14.4-15.5 million USD.

8) A full scale flow test and pilot system for fluid evaluation would cost 5.5 million USD.

Our modelling indicates that a ten-fold increase in power output per well, relative to that from conventional geothermal wells 2.5 km deep is likely if fluid is produced from reservoir hotter than 450°C. This is because supercritical fluids have very low viscosity and density, so that extremely high flow rates should be possible from such wells. A comparison with a conventional geothermal well is instructive. A conventional well that produces dry steam only, at a wellhead pressure of 25 $bars_a$ and a downhole pressure of 30 $bars_a$ will yield approximately 5 MW of electric power if the volumetric rate of outflow from the well is 0.67 $m^3 s^{-1}$. An IDDP well tapping a supercritical reservoir with temperatures of 430 – 550 °C and pressures of 230 - 260 bar may be expected to yield 50 MW of electric power given the same volumetric inflow rate (Albertsson et al. 2003a, b). Drilling deeper wells to test this unconventional geothermal resource would also allow testing of injecting cold water into fractured rock to sweep heat from a very hot reservoir. Experiments in permeability enhancement could also be conducted.

Based on evaluation of the IDDP Feasibility Study in 2003, the energy consortium decided to proceed to select the location and design of the first exploratory wells and to seek international partners and funding. During that discussion one of the members of the Deep Vision consortium, Hitaveita Sudurnesja Ltd (HS), offered to allow IDDP to deepen one of their planned 2.5 km deep exploratory/production wells. It is located on the Reykjanes peninsula, where the Mid-Atlantic Ridges emerges from the ocean (Figure 1) and so is ideally located for scientific studies of the coupling of hydrothermal and magmatic systems on mid-ocean ridges. A comprehensive scientific program, involving investigators from more than 12 different countries, is therefore planned to take advantage of this unparalleled research opportunity.

The scientific studies require that as much drill core as possible, especially from the deeper part of the borehole in the supercritical zone. We plan to use the DOSECC Hybrid Coring System (DHCS) for coring that part of the well. The DHCS uses a small diameter mining type core barrel, type HQ, hole diameter 3 7/8 inches. Our original plan was to use this system in two phases from 2.5 to 3.7 km in 2005 and from 3.7 to 5.0 km in 2006. However coring is slower and more expensive than conventional drilling. Therefore, we submitted a funding request to ICDP (International Continental Scientific Drilling Program) in January 2004 to at least partially cover the additional drilling costs incurred in obtaining 1.2 km of core during the first planned phase of coring from 2.5 to 3.7 km depth. This slimhole would then be reamed to production size hole, e.g. to 8 ½ inches diameter, followed by cementing of a 7 inch wide liner, before the DHCS system would be used to continue coring to 5 km.

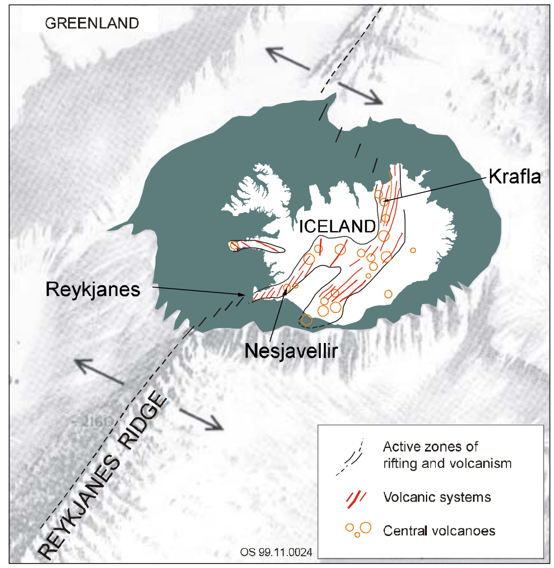

Figure 1: The location of Reykjanes Peninsula on the Mid-Atlantic Ridge at the South West tip of Iceland and the three geothermal fields Reykjanes, Nesjavellir and Krafla that are potential sites to develop supercritical geothermal resources in Iceland .

At the end of May 2004 the ICDP requested that the ICDP should clarify the scientific goals of the project and revise the work proposed in order to reduce the budget. Accordingly SAGA (Science Application Group of Advisors) of the IDDP, met with Deep Vision, the IDDP steering committee, and a number of international participants, on June 1st and 2nd. The report of this meeting, the 4th SAGA report, is available at the http://www.iddp.is. At this meeting, a representative of the industrial consortium reaffirmed that it is only a matter of time before the industry drills much deeper into the high-temperature zones in Iceland. Given the uncertainties of the budget at the time of the preparation of this paper, drilling and coring plans were still under active discussion, so that the drilling plan discussed here will doubtless be modified and improved as the project develops. The modified drilling plan discussed here would yield fluid samples from flow tests at depths 2.7, 4.0 and 5.0 km depths; pressure, temperature and flow-meter logs over the whole drilled intervals; drill cuttings down to 4.0 km depth, including several spot cores from 2.7-4.0 km depth, and continuous drill cores from 4.0 to 5.0 km depth. This plan is technically challenging and therefore expensive. Few boreholes in the world have ever been drilled at temperatures of greater than 400°C.

2. THE IDDP DRILLING PLAN

Our cost sharing models are based on the assumptions that the industrial partners would finance the cost of an exploration or production well, whereas the additional operational costs incurred by the scientists, such as coring, etc., would be financed by the science program. This was reflected in the drilling proposal submitted to ICDP that requested 4 million USD for continuous coring from 2.5 to 3.7 km depth. This sum represents the cost difference between rotary drilling and continuous coring from 2.5 to 3.7 km, plus the rig time necessary for specialized logging and fluid sampling for the science program and associated costs. The cost of drilling this hole from 2.5 to 3.7 km without coring, i.e. by conventional rotary drilling with an 8 1/2 inch bit was estimated to be 3 million USD, whereas continuously coring that interval and cementing a 9 5/8" casing down to 2.5 km was nearly 7 million USD.

The obvious way to reduce the incremental drilling costs for the science program is to reduce the amount of coring in a way that minimizes the negative impact on the science programme. The plan discussed here is such a compromise approach that emphasizes obtaining only the cores most vital to the science program.

The coring options range from (i) complete wireline coring from the surface down, (ii) wireline coring below 2.5 km, (iii) spot coring during rotary drilling, to (iv) no coring at all. Option (i) is too expensive, and does not take advantage of the 2.5 km deep well being offered by industry. Option (ii) was the option that was presented in drilling proposal to ICDP. Option (iii) is expensive of drilling rig time because of the number of round trips necessary to retrieve a core barrel and resume drilling. Depending on the number of trips of the drill string, it is estimated that attempting a single 8 m long core deep down in the borehole could cost up to 100,000 USD. The last option (iv), however, is basically unacceptable to the current science program for the several reasons discussed below.

2.1 The need for drill cores

A major aim of the science program of the IDDP is to investigate the transition from subcritical to supercritical conditions in an active hydrothermal system, to determine pressures, temperatures, and fluid compositions and to gain insight into the physics and chemistry of the supercritical state in nature. To investigate the systematics of magma-hydrothermal processes near critical conditions a major requirement is to obtain as much core as possible. Study of the coupling of the chemical and mineral alteration, fracture propagation, pressure solution, and fluid flow will be based on analysis of data on mineral chemistry, isotopes, geothermometry, and fracture geometry. More than half the science projects proposed to the IDDP would be impossible or severely compromised without drill core. Approximately 60 science projects have been proposed to participate, in the IDDP by scientists from USA, Canada, Iceland, Germany, France, Italy, Russia, New Zealand and Japan

The common practice in Iceland is to use downhole motors, for their high penetration rate while rotary drilling, and this produces very fine grained drill cuttings. Unraveling the nature and chronology of fracture failure and vein in-filling and detection of time serial fracture events and determination of constituitive rock properties requires core. Measurements of mechanical and thermal properties of core as a function of temperature are necessary to quantify processes related to brittle-ductile behaviour. The permeability and thermal diffusivity of fractured and intact, fresh and altered, basalt comprise essential baseline information for fluid circulation models.

Another compelling argument for coring is that due to high permeability, total loss of drilling fluid in geothermal reservoirs is often encountered in drilling Icelandic geothermal wells. While lost circulation is probably the best indicator of the high permeability, essential for geothermal exploitation, it prevents recovery of drill cuttings. Furthermore, high temperatures will preclude use of borehole televiewers, and many other logging tools. Thus drilling without core risks having no information on the strata penetrated. Coring is a part of all major scientific drilling projects today and the philosophy is that utilization of core will increase in the future as science progresses, as cores constitute a robust archival record.

A final argument for coring is that their study during drilling will provide useful information to guide the drilling and casing operations in real time. Mixing subcritical with supercritical fluid during production could cause acidification by wettening the steam and thereby lead to corrosion or scaling of the well casings. This can be avoided by casing off the sub-critical zone. This requires recognizing when supercritical conditions are encountered during drilling and before flow testing. This will be done by studying mineral assemblages and fluid inclusions in cores in an on-site petrographic laboratory. However, once the physical conditions of the deep reservoirs studied are known, normal production wells could be drilled without coring.

2.2 The drilling plan proposed in June 2004

The current drilling plan proposed in June 2004 is shown in Figure 2 and Table 1. In this compromise approach only spot cores will be taken during rotary drilling at depths above 4 km, e.g. at bit changes, and continuous wireline coring will only be done deeper than 4.0 km, that is in the hotter part of the system, where supercritical conditions are most likely.

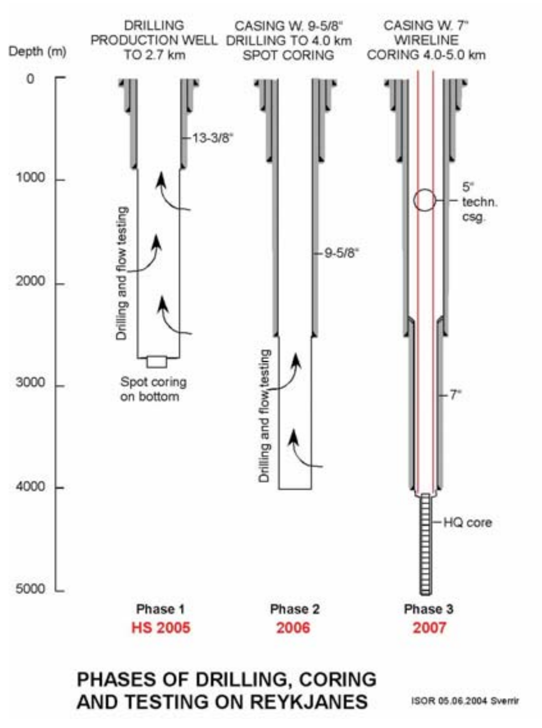

Figure 2. An alternative drilling plan for the IDDP borehole in the Reykjanes geothermal system.

The sequence of operations proposed is shown in Table 1 and described below:-

Phase I – Pilot Phase (0-2.7 km) Rotary Drilling: In February 2005 Hitaveita Sudurnesja intends to complete a bare-foot production well 2.7 km deep with 13 3/8 inch production casing to 800 m. One or two 8 meter-long spot cores will be drilled at 2.7 km depth, and a full suite of logs, including specialized high-temperature tools, will be run. A full-scale flow test will carried out in August to October. The cost of drilling, logging and testing the 2.7 km deep well, estimated to be about 3 million USD, will be paid by Hitaveita Sudurnesja. The incremental operational cost of the science program in 2005 is estimated to ~150,000 USD (rig time for coring, specialized logging, fluid sampling, onsite laboratory, etc.)

Table 1. Proposed work plan for an IDDP borehole at Reykjanes.

	Actions:	
DATE:		
2005	Rotary Drilling	Logging
Jan-Feb	Drilling with 12 1/4" bit	conventional
0.0 - 2.7 km	0.8-2.7 km open hole	plus high-T tools
		petrography & fluid -
	spot core at bottom	inclusions & DIS
Aug-October	Flow test 1	conventional
2006	Casing with 9 5/8"	conventional
Aug-October	Drilling with 8 1/2" bit	plus high-T tools
2.7 - 4.0 km		petrography & fluid -
	Core at bit changes	inclusions & DIS
		Initial corestudy
Dec-March	Flow test 2	As applicable
2007	Core drilling	Logging
Aug-October	Casing with 7"	HSDP-model
	Technical casing 5"	for core handling
4.0 - 5.0 Km	DOSECC coring 3.8" bit	
Nov-Dec.	Flow test 3	As applicable

Phase 2-(2.7-4.0 km) Rotary Drilling. Starting in August-October 2006, 9 5/8 inch casing will be cemented to 2.7 km and rotary drilling commenced with an 8 1/2 inch bit down to 4.0 km. Spot cores will be taken at bit changes, and high-temperature logs run. A flow test of the open interval 2.7-4.0 km will be carried out between December 2006 and March 2007. The time for drilling from 2.7 to 4.0 km in Phase 2 is about 50 days. The cost of rotary drilling is estimated to be about 3.7 million USD. The incremental operational cost of the science program in 2006 (spot coring, sample handling, specialized logging, fluid sampling, field laboratory, etc.) is estimated to be in the range of 0.5 million USD.

Phase 3 (4.0-5.0 km). Continuous Wireline Coring. Starting in August-October 2007, a 7-inch casing will be cemented to 4.0 km and wireline HQ drilling will start, through a 5-inch technical liner, using a mining type drilling rig (the DOSECC DHCS system). Coring from 4.0 to 5.0 km and testing, logging and downhole experiments would take about a hundred days and cost 5.5-6 million USD, which would be a charge to the science program in 2007, subject to negotiation with the energy consortium and possible international partners. A flow test from the cored hole of the interval below 4.0 km would also be attempted.

3. POSSIBLE WIDER APPLICATIONS

The IDDP needs international partners to participate in the high costs involved its research and development program, for scientific coring and the development and usage of the prototype high-temperature logging and downhole sampling tools needed for the project.

Today Iceland has the world's highest ratio of renewable energy, as 67% of all primary energy used is either hydro or geothermal. This fraction could become larger if techniques being developed to use renewable energy for the production of hydrogen, for land and sea transport, can be made economically feasible. The concept of using supercritical geothermal fluids as a power source that we will investigate in Iceland has potential applications wherever high-temperature geothermal reservoirs occur, for example, in New Zealand, Japan, Kamchatka, Indonesia, the Philippines, and the USA and in many other places around the globe where high temperature geothermal resources exist.

In Europe research groups from Turkey, Greece, Spain, Portugal, Netherlands and UK have submitted expressions of interest in the IDDP to the European Commission (EU). Their interest relates to a vital issue of finding sustainable energy resources within Europe. If unconventional geothermal resources with sufficiently high energy potential can be found within Europe, production of a clean energy carrier like hydrogen, could be considered to exploit them. The EU has emphasized the need for increased use of renewable energy, and has proposed a target of 15% of energy used should be renewable energy by 2010. If the target proposed by EU is to be achieved, very innovative research and development will be needed to fully develop available sustainable energy sources in Europe. We believe that the EU should develop a focused program of research on what we term: "Unconventional Geothermal Resources" (UGR), including geothermal reservoirs at supercritical conditions. Iceland has a number of advantages as the site of a test-bed for a research and development platform for such an international effort. An important part of an EU UGR programme should include a preliminary assessment of supercritical resources within the Europe and elsewhere. Supercritical sources may for example exist within Italy, Turkey, Greece, Spain (Canary Islands), Portugal (The Azores), and French Guadeloupe.

4. DISCUSSION AND CONCLUSIONS

Budgetary considerations required that the original plan for continuous core drilling below 2.5 km depth down to 5.0 km depth needed to be modified. We therefore plan to rotary drill down to 4 km depth. Depending on funding, a limited number of spot cores will be taken from within the 2.7 to 4.0 km depth interval. Then continuous coring is planned 4.0 km to 5.0 km depth, in the hottest part of the geothermal system. The first phase of drilling, a 2.7 km deep production type drillhole, with 12¼ inch diameter, will be drilled early in 2005. This well will be flow tested the same year. Depending on the funding situation, this well will then be deepened in two stages in 2006 and 2007. The well will be flow tested after each drilling phase, at 2.7 km, 4.0 km and 5.0 km depth. The incremental cost of this drilling plan ranges between 12-13 million USD.

The IDDP can serve as an ideal R&D platform for a European, and an international programme, on sustainable energy from Unconventional Geothermal Resources (UGR) that includes using supercritical geothermal resources. This UGR platform should attempt to integrate the generation of electric power, production of a clean energy carrier like hydrogen, production of other chemicals in an environmentally sound way as applicable, and eco-tourism as part of the "Geopark" concept. Within Europe, potential supercritical sources may for example exist within Turkey, Greece, Italy, Spain (Canary Islands), Portugal (the Azores), French Guadeloupe. However, the concept is applicable elsewhere in the world within the numerous high temperature geothermal fields around the globe. The success of IDDP would represent a major breakthrough in the technology and economics of the geothermal industry worldwide.

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