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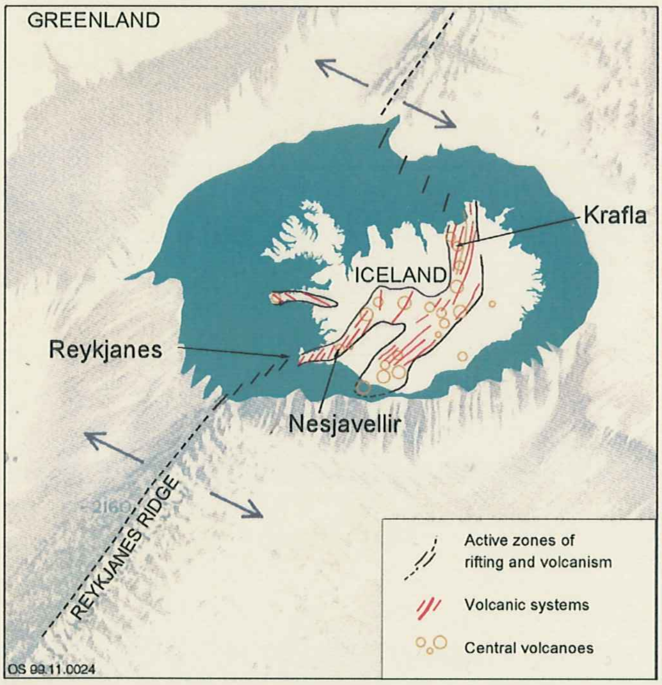
Iceland Deep Drilling Project

Feasibility Report



Part I Geosciences and Site Selection
Part II Drilling Technology
Part III Fluid Handling and Evaluation

Prepared for Hitaveita Suðurnesja, Landsvirkjun
and Orkuveita Reykjavíkur

May 2003
OS-2003/007

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Gudmundur Ómar Fridleifsson, (Ed.)

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Key page

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Prepared for:

Hitaveita Suðurnesja, Landsvirkjun and Orkuveita Reykjavíkur

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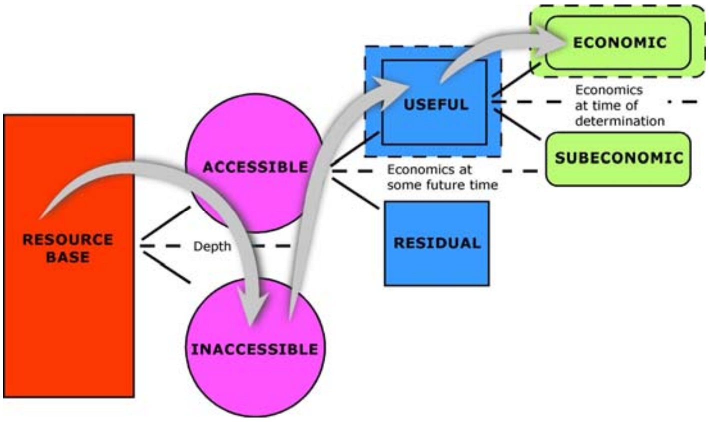
Abstract:

A consortium of Icelandic Energy Companies is investigating the feasibility and economics of drilling 4-5 km deep boreholes into active high-temperature hydrothermal systems with the aim of reaching a 400-600°C hot supercritical hydrous fluid. The consortium funded the feasibility study, while the International Continental Scientific Drilling Program (ICDP) has provided financial support to organize a science program, the establishment of the SAGA advisory group and three international workshops. The chief recommendations of the feasibility report are: 1) A full size vertical well should be drilled with a two-phase coring program; the earlier from 2.4-3.5 km depth; the latter from 3.5-5 km, after having reamed the hole and cemented a production casing. 2) As an alternative, the deepening of existing “wells of opportunity” down to 4 km should also be considered at this time. A CD-disc attached to this report, includes the report itself and material presented at the three workshops.

Key words: Deep drilling technology, geosciences and scientific coring, fluid handling and evaluation of supercritical hydrous fluids	**ISBN-number:** 9979-68-118-7 **Project manager’s signature:** **Reviewed by:** The Energy Companies, and SAGA

EXECUTIVE SUMMARY

The fundamental purpose of the Iceland Deep Drilling Project (IDDP) is to find out if the ***accessible*** part of the geothermal ***resource base*** can be enlarged significantly at the expense of the ***inaccessible*** part, in order to increase ***useful** and **economic*** exploitation of geothermal energy. The arrows in the McKelvey diagram below show this schematically.



Potential Benefits of the IDDP:

1. **Increased power output per well, perhaps by an order of magnitude, and production of higher-value, high-pressure, high-temperature steam.**
2. **Development of an environmentally benign, high-enthalpy energy source below currently producing geothermal fields.**
3. **Extended lifetime of the exploited geothermal reservoirs and power generation facilities.**
4. **Re-evaluation of the geothermal resource base.**
5. **Industrial, educational, and economic spin-off.**
6. **Knowledge of permeabilities within drillfields below 2 km depth.**
7. **Knowledge of heat transfer from magma to water.**
8. **Heat sweeping by injection of water into hot, deep wells.**
9. **Possible extraction of valuable chemical products?**
10. **Advances in research on ocean floor hydrothermal systems.**

IDDP intends to test the concept that producing supercritical high-enthalpy hydrous fluids in natural settings has economic benefits over producing conventional geothermal fluids, which are two-phase mixtures of liquid and steam. Modelling indicates that under favourable conditions, a 4-5 km deep well producing supercritical fluids at temperatures significantly greater than 450^{o}C could yield sufficient high-enthalpy steam to generate 40-50 MW_e. That is an order of magnitude greater electrical power output than is usual from a conventional 2 km deep well producing from a subcritical, liquid-dominated geothermal reservoir in Iceland.

While supercritical fluids are believed to exist deep within most of the active high-temperature systems in Iceland, only three or four exploited drill fields are sufficiently well studied to warrant siting 4-5 km deep wells to reach supercritical targets. Based only on consideration of their favourable geoscience criteria, the best locations, in order of priority, are at Nesjavellir, Krafla, and Reykjanes. However, all three sites are attractive, and 4-5 potential drillsites have been selected within each of these fields. The highest ranked drillsites in each field are: (i) A new well near NJ-12 at Nesjavellir; (ii) A new well near Hveragil in Krafla; and (iii) Deepening of RN-12 at Reykjanes.

At pressures and temperatures greater than the critical point, the difference between water and steam disappears and only a single fluid exists, that has high enthalpy and low viscosity. The critical point of pure water occurs at a temperature of 374.15 °C and a pressure of 221.2 bar. In systems where fluid pressures are hydrostatic, the critical pressure would be reached at 3.5 km depth. For geothermal fluids containing dissolved chemical components, the critical point is elevated above those values. Modelling indicates that the reservoir temperature at 5 km depth must be higher than 450°C, if the enthalpy of the fluid at the wellhead is to exceed that of steam produced by conventional geothermal wells. Such wells can be drilled safely by using existing technology, modified as necessary to cope with high temperatures. The drilling strategy proposed for the first IDDP wells, is to combine conventional rotary drilling with “slim-hole” wireline coring in order to achieve the twofold goal of completing a cased well to 3,500 m and obtaining rock samples that permit proper characterization of the largely unknown geological conditions at greater depths than 2,400 m. It is recommended that coring should be carried out in two steps, from 2,400-3,500 m and from 3,500-5,000 m. Below 3,500 m depth, it is planned that the IDDP well will be core drilled only (hole diameter of 98 mm (3.85″)).

During flow testing and fluid sampling, the production casing would be protected by an instrumented and retrievable, 4″ diameter, solid liner (referred to as “the pipe”). When this preliminary testing phase is completed, and more is known about the physics and chemistry of the produced fluid, a suitable pilot plant would be designed and constructed.

The IDDP is an expensive undertaking. A 5 km deep well with 9 5/8″ casing to 3.5 km is estimated to take up to 270 days to drill, and cost US$ 14.4-15.5 million (see Table 1). Furthermore, the cost of deploying “the pipe” and carrying out the fluid sampling program is estimated to be about US$ 5.5 million. Several less expensive options are also considered in the report. Depending on the specific design and depth, the costs of the alternatives for such a pilot hole range from US$ 6-9 million. Several drilling alternatives are listed in Table 1 below. These include deepening one or more existing wells, or “wells of opportunity”. The cost estimates presented below, only deal with drilling and well testing costs, but not potential incremental costs. For instance, it is as yet not known if environmental restrictions in some of the drill fields being considered would require the drilling of new disposal wells, and this is not accounted for here. In other geothermal fields, disposal wells or other disposal methods may be already available or applicable.

Table 1: *Cost estimates of drilling alternatives.*

	IDDP type B		IDDP type A		KJ-18 (4000 m)		RN-12		Well B - No core	
	Cost $	**Time**	**Cost $**	**Time**	**Cost $**	**Time**	**Cost $**	**Time**	**Cost $**	**Time**
Drilling	6.500.000	98	7.600.000	112	1.300.000	21	3.100.000	45	7.600.000	133
Coring	5.900.000	140	5.900.000	140	3.600.000	91	5.900.000	140	0	0
Logging, testing	700.000	20	600.000	18	400.000	12	600.000	16	300.000	11
TOTAL Base Est.	13.100.000	**258**	14.100.000	**270**	5.300.000	**124**	9.500.000	**201**	7.800.000	**144**
Contingency 10%	1.300.000		1.400.000		500.000		1.000.000		800.000	
TOTAL	**14.400.000**		**15.500.000**		**5.800.000**		**10.500.000**		**8.600.000**	

The main concerns about potential risks involve the exceptionally high temperatures and pressures at depths, and uncertainties about the fluid composition. Experience in deep drilling and coring under such hostile conditions is very limited, but in order to minimize the risk due to this lack of direct experience, the concept of core drilling from an existing well, or a phased programme of a core drilling project is deemed more favorable.

The "pipe" will mitigate potential risks from hostile chemical compositions. Model calculations indicate that if the reservoir temperature is above 450°C, the fluid at surface will be superheated steam, hotter than 350°C, and at a pressure approximately 90 bars lower than the reservoir pressure. The role of the "pipe" during flow tests is to minimize the risk of losing the well due to rapid corrosion or scaling. Because the existing casing is too narrow in some existing "wells of opportunity", like wells KJ-18 and NJ-12, those wells could not be completed with the "pipe", nor deepened to greater depths than 3.5-4 km. Other existing wells, such as RN-12 at Reykjanes, are wide enough to be cored and completed according to the proposed IDDP plan.

The chief recommendations of the IDDP feasibility study are therefore:

1. A full-size vertical well should be drilled with a two-stage coring program. Phase 1 involves drilling to 2,400 m, cementing an appropriate casing, and then continuous core drilling to 3.5-4 km depth. Phase 2 would involve reaming the well to insert the appropriate production casing to 3,500+ m, and coring to the target depth.
2. As an alternative, the deepening of existing "wells of opportunity" by core drilling should be considered seriously at this time. The options for wells of opportunity need to be identified before selecting the most suitable wellsite for such a pilot hole.

If the Iceland Deep Drilling Project meets the goal of drilling up to 3 deep drillholes during the next decade or so, and a significant increase in power output per well is realised, e.g. by an order of magnitude, a new principal question arises. Can the total power output per geothermal field be significantly increased, say by a factor of 3 or 5? Most scientists would expect that there is a limit to maximum output from a geothermal field, and that it would vary between fields. However, we do not know the real limiting factor. Today, the electric power output of each of the three drillfields being considered is estimated to be close to 100 MW_e.

Increasing this by a factor of 3 to 5 would have a favourable impact on the economy and the environment for those fields. The estimated cost of a conventional 5 km deep hole drilled by a conventional rotary rig, without coring, is US$ 8-9 million, or about 3 times more expensive than a conventional production drillhole to 2 km depth.

Although the super deep IDDP wells are designed to investigate the economics of producing supercritical fluids they will also provide an unparalleled opportunity to experiment with deep reinjection of water in order to enhance the performance of the overlying hydrothermal systems. The wells will be drilled through fractured rocks, towards the heat sources of vigorously active high-temperature hydrothermal systems, within an active spreading zone. This should be an ideal environment for reinjection, and if it works here, it should work in similar kinds of geologic settings elsewhere. The IDDP well completion process, from Phase 1 testing, to Phase 2, followed by flow testing with or without the pipe, may extend for some years. Injection tests, e.g. with the aid of tracers, should become a part of that well testing process. This important aspect of the project is not dealt with in detail in this report. Such a reinjection program can be designed once more is known about the composition and properties of the deep fluids and the characteristics of the deep reservoirs.

In addition to the potential economic benefits, there is worldwide scientific interest in the IDDP, as drilling into supercritical conditions will permit studies of a broad range of important scientific issues. The range covers investigation of the development of a large, igneous province, and the on-land magmatic and fluid circulation character of the Mid-Atlantic Ridge, to investigations and sampling of fluids at supercritical conditions - aspects of high-temperature hydrothermal systems that have rarely been available for direct observation. In addition, the IDDP will require the use of techniques for high-temperature drilling, well completion, logging, and sampling. These techniques will have the potential for widespread applications in drilling into both oceanic and continental high-temperature hydrothermal systems. The IDDP project opens up the opportunity for a very comprehensive scientific program investigating the anatomy of a mid-ocean rift zone, by tying together land–based and ocean-based deep borehole studies with complementary geological, geophysical, and seismic imaging studies - putting the drilling activities into a broad regional, geological context.

A work plan for the continuation of the IDDP is presented below in Table 2, which would be implemented if the decision of the energy companies, backed up by Icelandic energy- and research authorities, is to proceed. Depending on funding, the time interval between Phase 1 coring and Phase 2 coring, as shown in the workplan, can be made shorter or longer. It should also be noted that coring a well of opportunity would, in some cases, only involve Phase 1 coring.

Table 2: *IDDP Work Plan – Scenario 2001-2007.*

Activity		2001								2002								2003												2004												2005												2006											
		J	F	M	A	M	J	J	Á	J	F	M	A	N	O	N	D	J	F	M	A	M	J	J	Á	S	O	N	D	J	F	M	A	M	J	J	Á	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Deep Vision, decisions																							1			2	2	2											3					4							3					4									
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Drilling-Phase 1																																												4			🟩	🟩	🟩	🟩	🟩														
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PI-meetings							▩					▩			▩											🟥	🟥			🟥					🟥						🟥			🟥			🟥						🟥			🟥			🟥						🟥
SAGA-meetings							▩					▩			▩																				🟥									🟥												🟥									🟥
Workshops							▩					▩			▩																																									🟥									🟥
Science activity & funding																																				🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	4	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	4	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Explanation :

🟪 **Feasibility report and science planning**
🟨 **Preparation for drilling, permitting, soliciting bids**
🟩 **Drilling-Phases 1 and 2**

▩ **ICDP funded**

🟥 **Not yet funded**

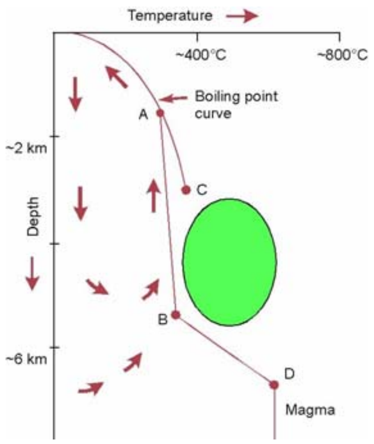
Decision points :
1: Review of plans
2: Funding for preparation
3: Funding for drilling
4: Kick-off meeting

Acknowledgements

The authors of this report would like to thank the Icelandic Energy Companies for the marvellous opportunity to deal with the challenge represented by the concept of the IDDP. We would also like to acknowledge the SAGA members for their valuable scientific input, and their domestic and foreign companies and institutions for allowing their participation in developing the IDDP. We also thank the many participants in the three IDDP/ICDP Workshops, from 12 nations, for their technical and scientific contributions and vigorous discussions. We are most grateful for the financial support from the International Continental Scientific Drilling Program (ICDP), which enabled the establishment of the international forum around the IDDP. Our thanks also go to the Icelandic Minister of Industry, Mrs. Valgerður Sverrisdóttir, and her Ministry for their goodwill and support. And finally, to the two co-PI's and SAGA members, professor Wilfred A. Elders, of the University of California, Riverside USA, and professor Seiji Saito of Tohoku University, Sendai, Japan, we extend our sincere thanks for their contributions and assistance in promoting the IDDP internationally since its inception. To this we have to add our deepest condolences to professor Seiji Saito's family upon his untimely death in March of this year.

FOREWORD

An Icelandic energy consortium is preparing the drilling of a 4-5 km deep drillhole into one of its high-temperature hydrothermal systems, at a rifted plate margin on a mid-ocean ridge, to reach hot supercritical hydrous fluids of 400-600°C. The green field in the drawing to the left delineates the hydrothermal field of interest. Icelandic energy companies (Hitaveita Suðurnesja, Landsvirkjun and Orkuveita Reykjavíkur) financed a feasibility study, leading to this report, while the ICDP (International Continental Scientific Drilling Program) granted financial support to organize the scientific program. An IDDP/ICDP start-up meeting was held in Reykjavík in June 2001, leading to the establishment of an international Science Application Group of Advisors (SAGA). This was followed by a drilling technique workshop in March 2002, and a science workshop in October 2002. The results of these workshops are described in SAGA Reports 1, 2 and 3. The workshops influenced the present feasibility report ably, and focused its approach in many aspects. The CD disc accompanying this feasibility report includes power point presentations, abstracts and outlines of research proposals presented at these workshops.



The feasibility report is divided into three parts. **PART I** deals with ***geosciences and site selection***. **PART II** deals with ***drilling technology*** and **PART III** deals with ***fluid handling and evaluation.***

Potential Drillsite for IDDP

REYKJANES

The Reykjanes Peninsula is the landward extension of the Reykjanes Ridge and encompasses a high-temperature hydrothermal system in a "ridge-crest" graben system. The depth to the oceanic layer 3 is unknown but a volcanic eruptive fissure zone of late Holocene age is targeted at 3-5 km depth, and/or the centre of the graben. The last volcanic eruption was in 1226 AD. The geothermal fluid is derived from sea water.

NESJAVELLIR

The Nesjavellir high-temperature hydrothermal system is associated with a relatively young central volcanic complex on the mid-Atlantic ridge system in SW-Iceland. During drilling in 1986 temperatures above 380°C were met at 2.2 km depth in well NJ-11 adjacent to a volcanic eruptive fissure zone. Because of a subsurface blow-out, the well was plugged up to 1.6 km depth (and this hostile situation has not been dealt with since). The geothermal fluid is of meteoric origin. One of the most attractive drilling targets for the IDDP at Nesjavellir is to re-enter the upflow zone that well NJ-11 encountered.

KRAFLA

The Krafla high-temperature system lies in an evolved central volcanic complex on the mid-Atlantic ridge system in NE-Iceland, involving a caldera and a large cooling magma chamber at shallow depth under an exploited drill field. Magmatic gases released during a volcanic episode that took place 1975-1984 seriously affected the well field and disturbed the exploitation. The gas emission has now ceased and well field possibly better than before. A cooling magma chamber is believed to lie at a depth of 3-5 km depth. The geothermal fluid is of meteoric origin. The main upflow zone in Hveragil is the most attractive drilling target for an IDDP well.

Iceland Deep Drilling Project

PART I

Geosciences – Site selection

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Knútur Árnason, Ingi Þ. Bjarnason, Gestur Gíslason

May 2003

SUMMARY

Over the next several years the 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. This requires drilling to depths greater than 4 to 5 km, in order to produce hydrothermal fluids at temperatures of 400 to 600°C. The aim of Deep Vision is to enhance the economics of geothermal resources by producing supercritical hydrothermal fluids.

Deep Vision launched a two year feasibility study early in 2001, in which basic questions should be addressed, such as: Can such a deep and superhot well be safely drilled?; can it produce fluids?; what will be the gains and losses, and the overall economics?; where should the first IDDP well be drilled, and so on. The feasibility report is split into three parts, Part 1 on geosciences and site selection, Part 2 on drilling techniques, and Part 3 on fluid handling and evaluation.

In this Part 1 of the report, the geological condition of the three high temperature hydrothermal systems is described; the Reykjanes system within the rift zone astride the Reykjanes Ridge, containing saline fluid; and the geothermal systems within the Hengill and the Krafla central volcanoes, both containing dilute fluids. Sixteen potential drill sites for IDDP wells are evaluated and discussed, and a priority order on site selection is made, both within each system and between them. The recommended IDDP priority order, i.e. which system to drill first is: Nesjavellir, Krafla, Reykjanes. Feasible targets exist within each of these geothermal systems, and the priority order is not meant to exclude the first IDDP drillhole to be sunk in any of them. Nevertheless, supercritical conditions are believed to exist at the shallowest depth attainable at Nesjavellir, and most likely involving the most dilute fluid of the three systems.

The heat source at Reykjanes is apparently rather deep-seated and for that reason relatively deep drilling may be needed to reach supercritical conditions. Bottom hole temperatures from well RN-12, a new 2.5 km well, are expected within the next few months, and will be a good indication of the deep temperatures to be expected. The fluids encountered so far in that system are relatively saline and there is no reason to expect deeper fluids not to be saline too. Other factors being equal higher pressure and temperature and therefore greater depth are needed to reach supercritical conditions if the fluid is saline than if it is dilute. A new well should be drilled at the Stampar eruptive fissure and compared to the well RN-12 prior to final siting of an IDDP well at Reykjanes.

Investigation of the Hengill volcanic complex indicates that supercritical conditions at shallower depth than 5 km, and perhaps less than 3 km depth, are likeliest to be found associated with the youngest volcanic structure in the western part of the Nesjavellir system. If the fluid in this main upflow zone at Nesjavellir is dilute fluid of the type observed elsewhere in the Nesjavellir system, the satellite nature of the system as an outflow from the Hengill center, makes it likely that the fluid has reached some sort of equilibrium after magmatic gases were emitted from the magma reservoir and therefore the fluids are not likely to be vicious. Accordingly it is likely that at Nesjavellir supercritical conditions can be reached at a relatively shallow depth with minimum danger of utilization problems. A new inclined well near NJ-12 in Kýrdalur, is recommended, aiming to meet a supercritical zone at 3-4 km depth, while other options are considered.

The heat source in Krafla is believed to be shallow and high temperatures are expected be reached at relatively shallow depths. The closeness to a magma chamber may possibly bring problems such as those encountered during the 1975-1984 episode, manifested in extensive deposits and acid fluids, even though the effect of the volcanic episode has diminished substantially in recent years. The reservoir fluid is apparently dilute and easy to handle but there are signs from one well (KJ-12), which temporarily charged superheated fluid, that at a greater depth there may exist a more saline brine from which HCl-rich steam can boil. The main upflow zone at Hveragil is the most attractive target. Whether the well will be straight or inclined, has not yet been discussed seriously, but both options should be considered. The presence of a supercritical fluid above 4 km is most likely the case.

In developed crustal genesis regions of Iceland, like at the proposed sites for the IDDP at Reykjanes, Krafla and Hengill, it is hypothesized that the onset of semi-brittle state in crustal rocks occurs at the top of the lower crust. At approximately this depth the frequency of earthquakes starts to drop. It lies at 4-5 km depth under the IDDP sites. The depth above which 90 % of the seismicity lies, is defined as the depth to the brittle-plastic boundary and the bottom of the seismogenic part of the crust. This boundary lies between 6 and 7 km below the IDDP sites with a 1.5-2 km thick brittle-plastic transition zone above it. There are limited laboratory measurements available on rheology of basaltic rocks, but arguments have been put forward for a 600°C temperature at the semi-brittle boundary and 760°C at the brittle-plastic boundary in a 2 cm/yr strain region like Iceland. None-double couple earthquakes in the midcrust and in the top part of the lower crust in crustal genesis regions of Iceland suggest that hydrous phases may exist in the crust at depths where the average temperature exceeds 400°C. Expected temperatures at all IDDP drillfields considered, range between 550 and 650°C at 5 km depth, +/- 100°C.

A review of environmental verdicts from the Planning Agency in Iceland, shows that drilling itself is usually not the main environmental concern but rather activity such as road construction and excavation of material. As all IDDP boreholes proposed will be located within borefields belonging to an approved power plant, and/or involve deepening of an existing borehole in such a field, it is likely that road construction and other surface disturbances will not cause serious environmental concern. The main geothermally related concern is the disposal of waste water from boreholes, either during testing or utilzation. When the IDDP project will be evaluated, the disposal of waste fluids is likely to cause concern, as the purpose is to obtain fluid which we are not familiar with and might well contain various elements in higher concentrations than is desirable for the environment, unless preventive action is taken. However, as detailed knowledge of the deep fluid composition will never be available without deep drilling and flow testing, the chief concern should be to secure the strategy for safe disposal of the fluid during testing. As the IDDP wells should produce superheated dry steam and gases, the liquid fluid portion would mostly be condensate, ans should constitute a small volume.

The next step to be taken regarding IDDP depends entirely on the Icelandic energy companies. Firstly, each company must decide if their drill fields, or parts of them, will be made available for IDDP drilling. Secondly, when the first decision is available, a decision on where to drill the first well need be made. Thirdly, a decision on if and when to continue need be made. If the third decision will be to continue IDDP, and the decision is not delayed for too long, the next logical step is to seek local and international partners and funding for the drilling and science activity. Once the potential IDDP target has been selected, there is need for a series of preparation and planning processes for the drilling and science organization, funding being the most important. Applications for funding from international funding agencies or the industry take time. Two years do not seem unrealistic.

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TABLES:

FIGURES

1 INTRODUCTION

The **Iceland Deep Drilling Project (IDDP)** is a project of **Deep Vision**, a long-term, focussed program to improve the economics of electrical production by major improvements, in the power output of geothermal wells. The study will require drilling wells and sampling fluids and rocks to depths of 3.5 to 5 km and at temperatures of 400-600°C. The long term IDDP plan is to drill a series of deep boreholes to penetrate into supercritical zones believed to exist beneath three currently producing high temperature geothermal fields in Iceland. The main aim is to produce fluids for electrical power production that have significantly higher enthalpies and flow rates than are currently available to the worldwide geothermal industry. If such enormous gains in energy output from supercritical reservoirs can be obtained, it would enable the geothermal energy industry to exceed current estimates of its potential for meeting long-term energy demand by a substantial amount, not only in local or regional markets, but globally. Current estimates of potential geothermal contributions to global energy demand are in the range of a few percent of total installed electrical power. A five- to ten-fold increase in energy output per well from high-temperature geothermal reservoirs would make the economics of geothermal energy more competitive globally, particularly in conjunction with a hydrogen-fuelled transportation system in countries like Iceland that lack sources of hydrocarbon fuels. Therefore, the success of this project can have important environmental as well as scientific benefits.

Deep Vision is a consortium of three major energy companies in Iceland, Hitaveita Sudurnesja (HS), Landsvirkjun (LV) and Orkuveita Reykjavikur (OR), together with Orkustofnun-GeoScience (ROS), a research division of the National Energy Authority of Iceland, a government agency. Representatives from these companies constitute the Deep Vision steering committee, Albert Albertsson (HS), Björn Stefansson (LV), Einar Gunnlaugsson (OR) and Gudmundur Omar Fridleifsson, (ROS) respectively. Deep Vision was established in early spring 2000, and the IDDP long term goal of drilling for supercritical hydrous fluid presented at the World Geothermal Congress in Japan early summer the same year (Fridleifsson and Albertsson, 2000). There, a call was made for an international collaboration around the idea of deep drilling for supercritical fluid. A group of three principal investigators (PI's) was established, in addition to G.O.Fridleifsson, composed of Wilfred A. Elders, emeritus professor and the University of California, Riverside, USA and professor Seiji Saito at Tohoku University, Sendai, Japan.

Deep Vision launched a two year feasibility study on IDDP in March 2001, to examine three candidate sites in Iceland and to consider the economic and engineering issues of drilling to greater depths and higher temperatures than are currently drilled. Three thematic working groups were established, one on ***geosciences***, another on ***drilling technique*** and the third on ***fluid handling and evaluation*** (earlier pilot plant group). These were led by Gudmundur Omar Fridleifsson, geologist, Sverrir Thorhallson, drilling engineer, and Albert Albertsson, mechanical engineer, respectively. The mandate of the groups varied considerably and, was estimated to be by far the most extensive for the drilling technology group. The **role of the geosciences group (GS-group)** was mostly to review existing data on the different geoscientific aspects of the three high-temperature hydrothermal systems being considered, Reykjanes (managed by HS), Nesjavellir (managed by OR) and Krafla (managed by LV) with respect to deep drilling. Based on this review process a recommendation on potential IDDP drillsites in all these systems was to be made, and if pertinent, a selection of a site for the first IDDP drillhole. Additionally, a review of environmental aspects and relatively recent environmental legislation, became the role of the geosciences group. The principal **role of the drilling technique group (DT-group)** was to answer the fundamental question if drilling for 400-600°C hot hydrous fluid, and its production through the wellbore, was possible with respect to a variety of safety measures, both during and after drilling. The second role of the group was to make detailed cost estimates of different drilling options for the IDDP drilling project. The **role of the fluid handling and evaluation group (FHE-group)** was to look into the technical aspects of utilizing a supercritical hydrous fluid from an active hydrothermal system. Can such a fluid be produced through a wellbore and what is the likely course of events upon cooling and depressurization. The three technical groups have worked relatively independently of each other in between three IDDP/ICDP technical workshops, discussed below. Therefore a decision was taken to present the **feasibility report** in three parts, **Part I on geosciences and site selection**, **Part II on drilling technique**, and **Part III on fluid handling and evaluation.** G.O Fridleifsson has served as the project manager for IDDP and a liaison person between the feasibility study groups.

At WGC-2000 in Japan, Deep Vision invited the participation of the engineering and scientific geothermal community to use these IDDP wells for both technical and scientific studies that are of mutual advantage to both industrial and scientific participants. An application for funding was submitted to the International Continental Scientific Drilling Program (ICDP) in January 2001. In early spring ICDP granted the PI's US $ 50.000 to organize and plan the science structure. An **IDDP/ICDP start-up meeting** was held in Reykjavik in June 2001. A ***Science Applications Group of Advisors*** **(SAGA)**, with both Icelandic and international membership was formed to develop the guidelines for a scientific program within the IDDP. The newly established thematic groups of the feasibility study introduced data and ideas on the three high-temperature systems concerned and the IDDP plans. The exchange of ideas with SAGA sharpened the focus of the feasibility study. The result of the start-up meeting is described in SAGA report No. 1 (see Appendix 1). Iceland enrolled as a member country of ICDP in December 2001. At a PI meeting in December 2001 it became clear that the IDDP program needed two workshops, one on drilling technique and another one on geoscience. A 2nd application to ICDP, now for workshop 2, was submitted to ICDP in January 2002. ICDP granted another US $ 50,000 support a few months later.

Workshop No. 1, was held in March 2002 and was concerned with optimising the strategy of drilling into and sampling at supercritical conditions. That workshop led to a clearer definition of the conditions likely to be encountered and developed guidelines for planning the necessary drilling, coring and fluid sampling. The result of Workshop No.1 is described in SAGA report No.2 (Appendix 1). The result of **Workshop No. 2**, which was held in October 2002, is described in SAGA report No. 3 (Appendix 1). The 2nd workshop was primarily concerned with formulating a comprehensive science plan and discussing research proposals submitted by the international science community to participate in IDDP. About 40 separate scientific proposals were considered at this workshop. Workshop No. 2, provided the framework for detailed planning of a scientific program integrated with the drilling and sampling strategy. The outcome was an enthusiastic endorsement of the project by both industrial and scientific partners.

Workshop No 2 was followed by a meeting of SAGA, the science advisory group of the IDDP. Specific recommendations of the SAGA meeting included (i) Performing an immediate review of existing geothermal wells in Iceland that could be utilised by the IDDP for scientific studies. (ii) Discussing opportunities for drilling and sampling of pilot holes to obtain scientific information and to test technologies for later use in the hot, hostile environment of the deep boreholes that will be drilled by the IDDP. (iii) Continued planning of and preparation for the long-term program of deep drilling.

During the IDDP/ICDP start-up meeting and workshops No.1 and 2 status reports of the feasibility studies were presented and discussed along with other topics. These discussions, and subsequent recommendation by SAGA, influenced the feasibility study and the overall drilling strategy. This is mirrored by cost estimates for different drillhole options in Part II of the feasibility report on drilling technology, and also by a somewhat extended discussion of the "wells of opportunity" in Part I of the feasibility report. In Part II, cost estimates are made for well types A and B, proper IDDP wells, and several different types for "wells of opportunity". Basically, a well of opportunity involves "pilot drilling" by coring between 2-4 km from some existing high-temperature well.

For decades, most of us working on the feasibility report have been deeply involved in research and exploration of all the three geothermal areas dealt with. As a consequence, in Part I of the feasibility report, we have the tendency to shortcut through the literature and unpublished data on Reykjanes, Hengill and Krafla, and extract only the essence of knowledge relevant to the long term goal of IDDP. Along with us, a number of colleagues at Orkustofnun, Geoscience, have summarized data on the high temperature systems and presented in lectures and field guidance during the start-up meeting in 2001 and at the IDDP/ICDP Workshops No.1 and 2 in 2002. In particular we want to acknowledge: Ásgrímur Gudmundsson, Benedikt Steingrímsson, Grímur Björnsson, Hjalti Franzson, Hjálmar Eysteinsson and Ómar Sigurdsson. Their contribution is adopted in the feasibility report as needed. Most of the abstracts and presentations made during the IDDP/ICDP workshops are also made available on CD-discs along with this feasibility report, and an inseparable part of it. Beside the Orkustofnun staff, geothermal experts from VGK-engineering Ltd, Iceland Drilling Company Ltd., and the energy companies, in addition to Deep Vision, have been involved in the feasibility part of the Iceland Deep Drilling Project.

A note on the ultimate goal of IDDP needs be introduced before continuing. The chief task of IDDP is to successfully produce a supecritical hydrous fluid through a wellbore. One fundamental requirement for a successful operation, is to prevent mixing of supercritical hydrous fluid with fluid at subcritical temperatures. If mixing occurs, a two phase flow would result, fluid flow rate through the wellbore would be reduced, and serious acidification of water droplets could result and cause severe corrosion of the steel casings and well head equipment. The simplest way to prevent this, is to separate by steel casings, the conventional part of a hydrothermal system from its supercritical part. In water dominated hydrothermal systems, the maximum temperatures at each depth are controlled by the boiling point with depth curve (BPD-curve) up to the critical point (CP). For pure water the CP occurs at 221.2 bars and 374.15°C, but at higher pressures (P) and temperatures (T) as salinity increases. As the density of water decreases with increasing T the critical point will not be reached until at 3,5 km depth in open hydrothermal systems at boiling point T (up to the surface), as is locally the case for the Reykjanes, Nesjavellir and Krafla systems. Exception may exist at shallower depths, if some form of a caprock or a pressure chamber separates the subcritical part of the system from the supercritical. Well NJ-11 at Nesjavellir would represent one such example if true supercritical conditions were met at about 2,2 km depth as claimed by Steingrimsson et al. (1990).

The difference between a conventional two phase high-temperature hydrothermal systems and supercritical systems are neatly explained in the enthalpy-pressure diagram shown in Figure 1 (from Fournier 1999). At temperatures and pressures above the critical point (CP), only a single phase, supercritical fluid exists. If a supercritical hydrothermal fluid (at A) with an enthalpy of about 2100 Jg^{-1} flows upward, decompresses and cools adiabatically it would reach the critical point (at B), and with further decompression separate into two phases, water and steam (E and D). The arrows to the left of the vertical line AB

(AE and AL) show possible pathways where upward flow is accompanied by conductive cooling so that supercritical fluid is transformed into hot water with, or without, boiling. This situation is representative of many high-temperature, water-dominated, geothermal reservoirs where typically boiling, induced by decompression, drives a thermo-artesian flow in a wellbore. Similarly the pathway H-D represents supercritical fluid that separates into steam and water at D and E, a situation representative of a vapour-dominated geothermal reservoir. Steam turbines in geothermal plants generate electricity by condensing the steam separated from the two phase system, which, depending upon the enthalpy and pressure at which steam separation occurs, is often only 20% of the total mass flow. The concept behind the Deep Vision program is to produce supercritical fluid to the surface in such a way that it is transformed directly to superheated steam along a path like F-G in Figure 1, resulting in a much greater power output than from a typical geothermal well, possibly an order of magnitude greater.

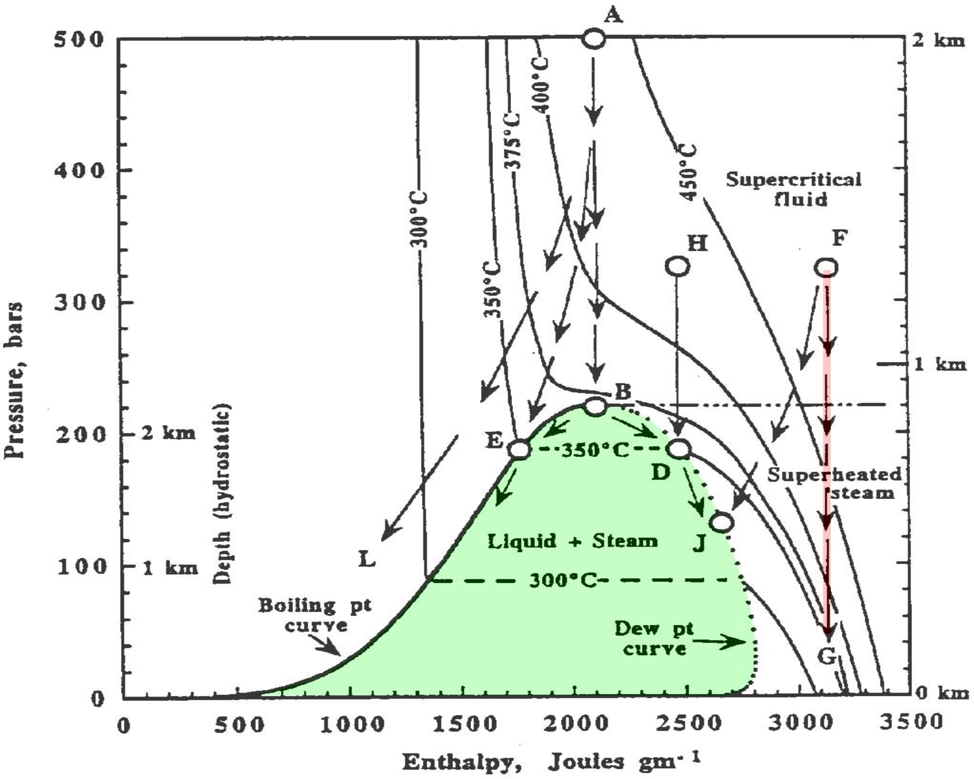

Figure 1. Pressure enthalpy diagram for pure H_2O with selected isotherms. The conditions under which steam and water coexist are shown by the shaded area, bounded by the boiling point curve to the left and the dew point curve to the right. The arrows show various different possible cooling paths (Fournier, 1999).

It should be noted that the pressure, enthalpy, and temperature limits on the two-phase field in Figure 1, will be affected greatly by salinity and the presence of non-condensable gases, such a CO_2 in particular. The effect of this, for instance, was discussed by Fournier at the IDDP-ICDP workshop 1, and by Tsuchiya and Bignall at IDDP-ICDP workshop 2, presentations available at the CD disc accompanying this feasibility report.

Considerable effort has been made in publicizing IDDP internationally and domestically since its beginning. In order to keep track of these, a reference to abstracts and publications to date is made (Fridleifsson and Albertsson, 1999, 2000; Albertsson and Fridleifsson 2000; Fridleifsson et al. 2000; Elders et al. 2001, a, b, c; Fridleifsson 2001, Fridleifsson et al., 2001 a, b, c, d, e; Fridleifsson et al. 2002 a, b; Saito et al. 2001, 2002; Thorhallson 2001), beside lectures and White Papers presented at the US–Iceland Science day, May 2002, lecture at the Soc.Sci.Islandica 2002, SAGA reports, 1, 2, 3, in 2001 and 2002 (Appendix 1), White Paper in relation to a possible application to EC-Framework Program 6, January 2003, and several presentations within the Deep Vision companies.

2 OVERVIEW ON REYKJANES, HENGILL AND KRAFLA

The three sites selected for consideration by the IDDP display different stages in the tectonic development of the mid-ocean ridge. The Reykjanes site, a direct on-land continuation of the submerged Reykjanes Ridge, represents an immature stage of rifting with a sheeted dike complex as a heat source. Fluids produced by 2 km deep geothermal wells in this system are evolved seawater. At Nesjavellir, the relatively young Hengill central volcano is the heat source for a geothermal reservoir in a graben recharged by meteoric water. The Krafla high-temperature geothermal field rests within a caldera in an active, mature, central volcanic complex, developed above a magma chamber. It produces evolved meteoric water with some addition of volcanic gases. Figure 2 shows the location of these three geothermal systems.

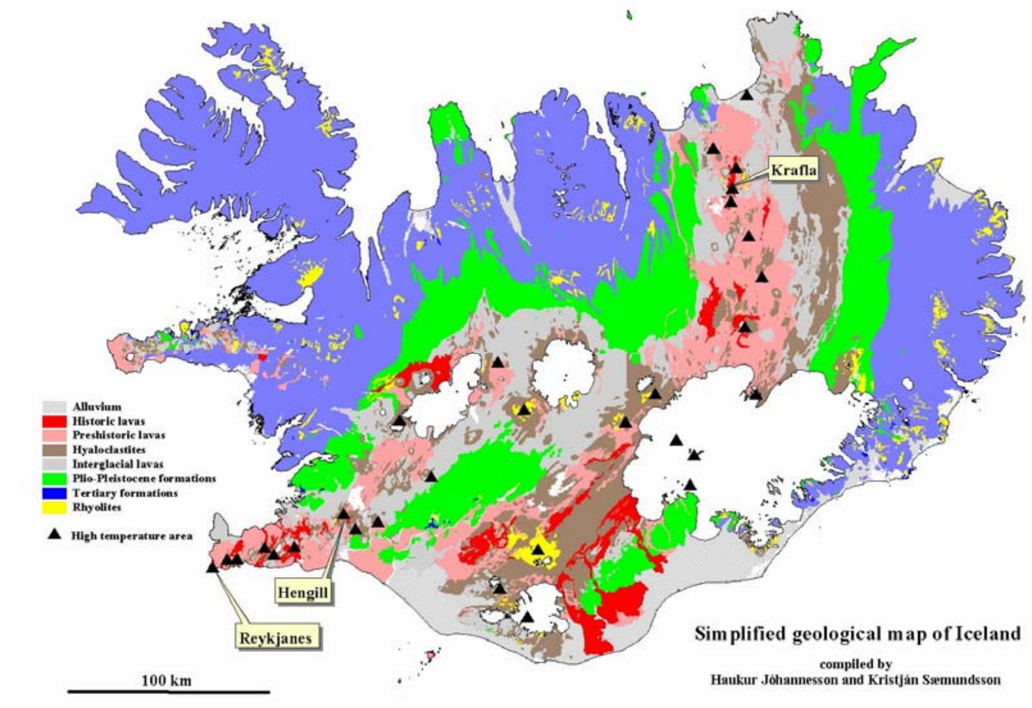

Figure 2. *Simplified geological map of Iceland showing the location of the Reykjanes, Hengill and Krafla high-temperature geothermal systems.*

First we present an overview of these high temperature areas. Closer details of the surface and subsurface geology and borehole geophysics, fluid geochemistry, resistivity, seismic studies and environmental aspects are dealt with in subsequent chapters. Most of our discussion is based on published and unpublished data, papers and technical consultancy reports to the energy companies (HS, LV, OR) on all the three areas. Most of the reports are in Icelandic and published by Orkustofnun, and in some cases others. Only a mere fraction of the reports is referred to here, and in general we limit the references list to significant published papers or published extended abstracts in English if available. An exception to this, concerns the seismic study done by Ingi Þ. Bjarnason in chapter 6. There a new interpretation on available seismic data is presented, e.g. on the depth to the brittle/plastic boundaries at all sites and the overall rheology of the crust, which is of particular importance to IDDP.

2.1 Reykjanes

The Reykjanes geothermal area is situated in the extreme SW of Iceland, about 50 km southwest of Reykjavík (Figure 2). There is a history of episodic hot spring activity there from early times (Sæmundsson 1997). Exploration of the area started in 1956 with the drilling of well RN-1, surface exploration phase followed, and an earthquake episode in 1967 gave valuable information. In 1968 wells RN-2-8 were drilled (Björnsson et al. 1971), well RN-9 in 1983, well Rn-10 in 1999, well RN-11 in 2001, and well RN-12 in 2002. Wells RN-8 and RN-9 have been regarded as extremely successful and have been used for a salt production plant but well RN-8 had to be closed down in 1993 due to a leak in a liner and deposits. Wells RN-10, RN-11 and RN-12 are still being tested, and data on reservoir temperatures and deep fluid composition is still limited.

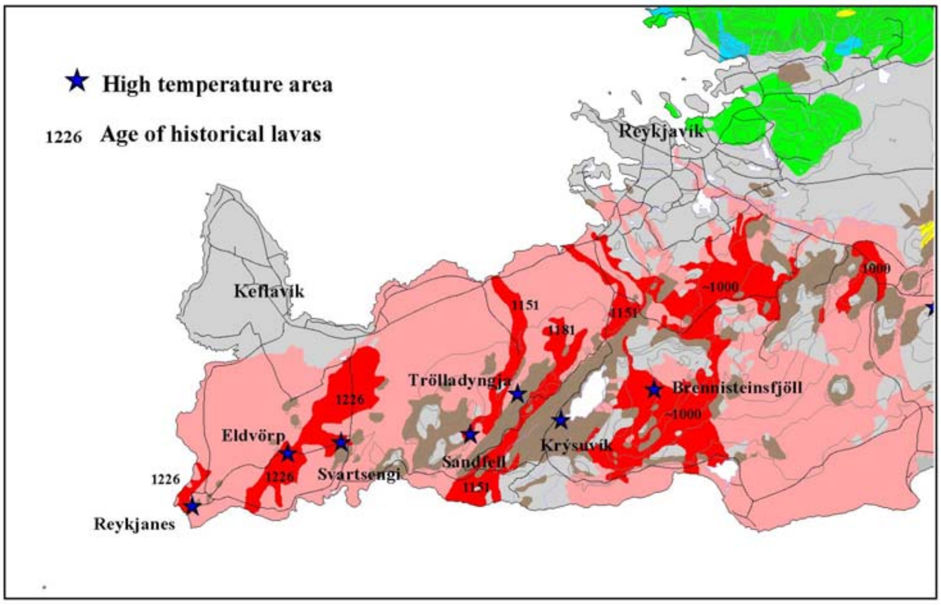

Figure 3. *Simplified geological map of the Reykjanes peninsula showing the distribution of historic lavas, and the distribution of active high temperature geothermal fields, like the Reykjanes field at the tip of the peninsula. The Trölladyngja field is mentioned in context of the wells of opportunities in later chapters.*

Figure 4 shows typical temperature profile for some of the drill fields on the Reykjanes peninsula. The Reykjanes field is the hottest system, where max. temperature at all depths is defined by the BPD-curve. The bottom hole temperature in well TR-01 at Trölladyngja is the highest measured in the fields shown, the well being 2300 m deep, and the bottom hole T only just below the BPD-curve. The deepest well at Reykjanes, and also the deepest high-T well in Iceland, is well RN-12, 2500 m deep. Knowledge of the true bottom hole temperature is expected within the next few months.

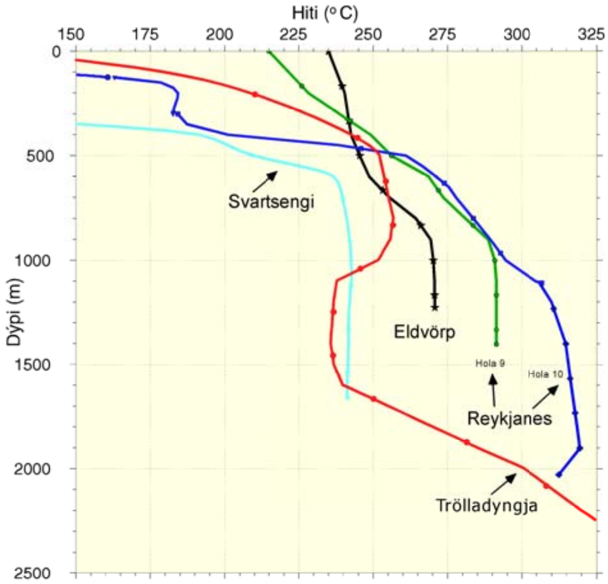

Figure 4. *Typical temperature profiles showing the reservoir temperatures at Svartsengi, Eldvörp, Trölladyngja and Reykjanes. The temperature of well 10 at Reykjanes is close to that defined by the BPD-curve.*

A closer detail of the geology of the Reykjanes field is discussed in Chapter 3. Some detailed surface exploration has taken place in recent years, both detailed geological mapping, and no the less detailed TEM-resistivity surveys (Chapter 6). A very important feature of those is the presence of low resistivity on top of high resistivity and the areal extent of such a feature is considered to delineate the high-T subsurface geothermal system. An overview of the resitivity at 500 m depth b.s.l. of the Reykjanes peninsula is shown in Figure 5.

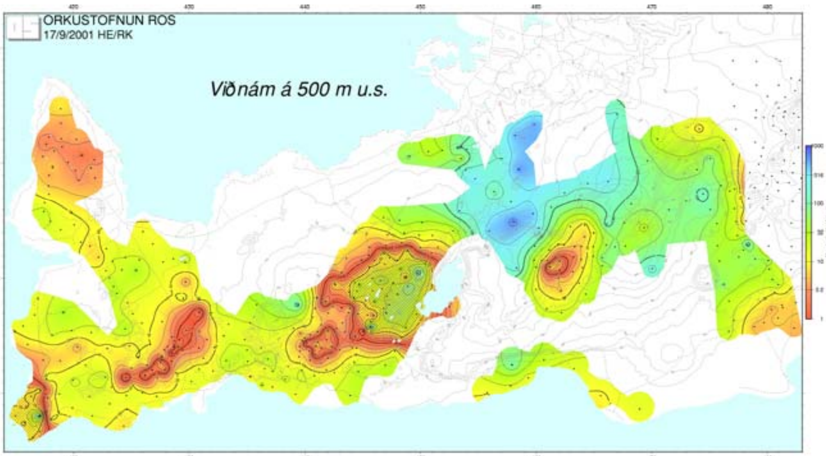

Figure 5. *An overview of TEM resistivity at 500 m.b.s.l on the Reykjanes peninsula. The Reykjanes high-T geothermal field is in the lower left corner.*

The results of recent resistivity measurements for the tip of peninsula (Karlsdóttir 1997) is discussed in more detail in Chapter 5, but they suggest an areal extent of at least 10 km^2 for the Reykjanes geothermal system whereas the extent of the surface surface manifestations is only about 1 km^2. The geothermal system is not restrained to the SW and it is quite likely that it extends for some distance in that direction below the sea-floor on the Reykjanes Ridge.

Seismology is a powerful tool to study and describe the nature of the earth's crust below drillable depths, and about the only tool available to predict the likely conditions at depths of interest to IDDP. In recent years development in seismometers and accumulation of digital data have enabled more detailed studies of the seismogenic crust. Such a study is described in Chapter 7. Figure 6 shows two examples of data accumulated during earthquake swarms in 1971-1976 (a), and 1991-2001 (b). Lack of a very recent seismicity within the Reykjanes geothermal system, and Krafla geothermal system, affects the feasibility study of seismicity to some extent while a very recent seismically active episode has affected the Hengill volcanic system (Chapter 7).

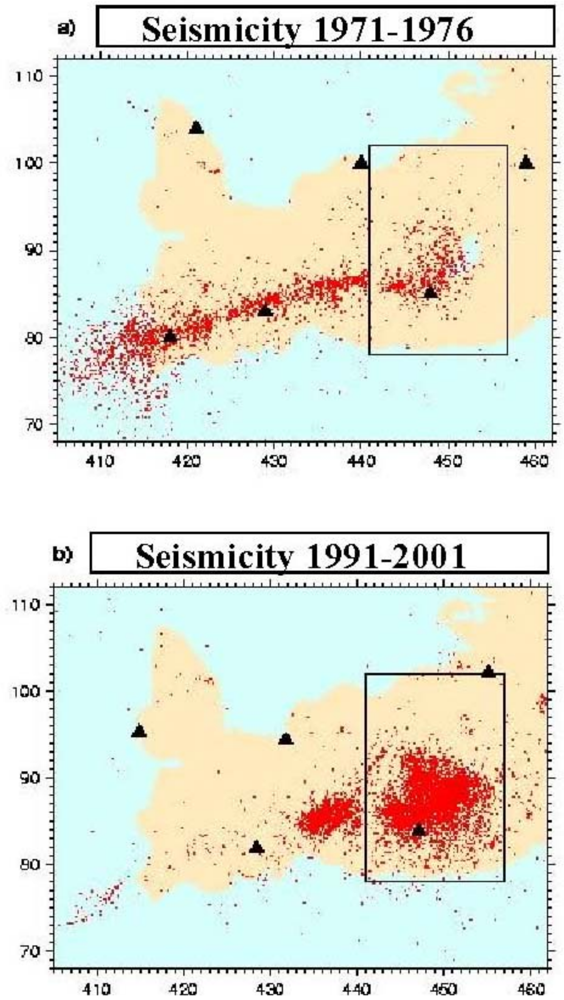

***Figure 6**. Seismicity during 1971-1976 (a) and 1991-2001 (b) on the Reykjanes peninsula. Data from the Meteorological Office.*

2.2 Hengill and Nesjavellir

The location of the Hengill central volcanic system is shown in Figure 2. The Hengill geothermal area covers about 100 km^2 according to results of geophysical measurements. The volcanic system has in recent year been divided by geophysicists into three "central volcanoes", overlapping and succeeding each other, the oldest one being the Hveragerdi-Grændalur center, active 300.000 to 700.000 years ago, and already eroded down to the chlorite zone; succeeded by the Hrómundartindur center, whose surface formations are younger than 115.000 years old; and the Hengill volcanic system which is presently active. Figure 7 shows a topographic map of the whole area, the distribution of geothermal manifestations and drillholes (mostly at Nesjavellir and Hveragerdi).

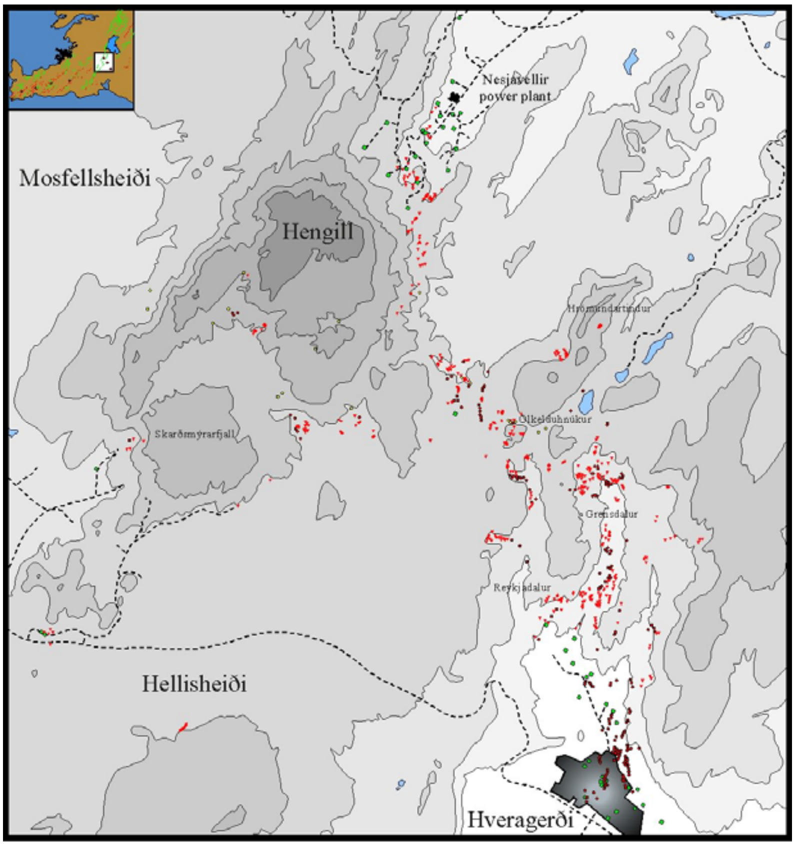

Figure 7. *A topographic map of the Hengill volcanic complex. The Nesjavellir part of the system is northeast of the Hengill mountain. Green squares indicate drillholes at Nesjavellir and Hveragerdi. Red spots indicate active fumaroles, spread over the Hengill complex and towards the Hveragerði town in the southeast. The distance from Nesjavellir to Hveragerði is about 12-13 km.*

Three high enthalpy geothermal fields, i.e. Hveragerði (including Grændalur), Ölkelduháls and Hengill respectively have developed within the three volcanic systems respectively. The geothermal fields of Nesjavellir and Hellisheiði are parts of the Hengill system. While convenient, this division into three separate central volcanoes is somewhat loosely defined geologically, and seems to relate rather to episodically active volcanic periods and local accumulation of volcanics at a shifting plate boundary, than separate systems. In many respects, it is more natural to look at the whole volcanic complex as an entity, slowly drifting away from the plate boundary. An interference with the south Iceland seismic zone (SISZ), which is of transform character, blurs the picture a little and affects the geothermal activity and possibly the volcanic activity as well. One such active episode started in 1994, and culminated in major earthquakes on the SISZ zone further to the east 17th and 21st June, 2000. The intense seismic activity during 1994-1999 in the Hengill area may have been caused by subsurface magma inflow in the Hrómundartindur volcanic system (Feigl et al. 2000). The Hengill system defined here with respect to IDDP, surrounds the Hengill mountain and the most active part of the fissure swarm crosscutting it. The Hengill mountain itself was mostly accumulated in one or two large subglacial eruptions during the last glacial period. Last summer, new geological data were presented that suggest the lower part of the mountain may have formed during the 2nd last glacial.

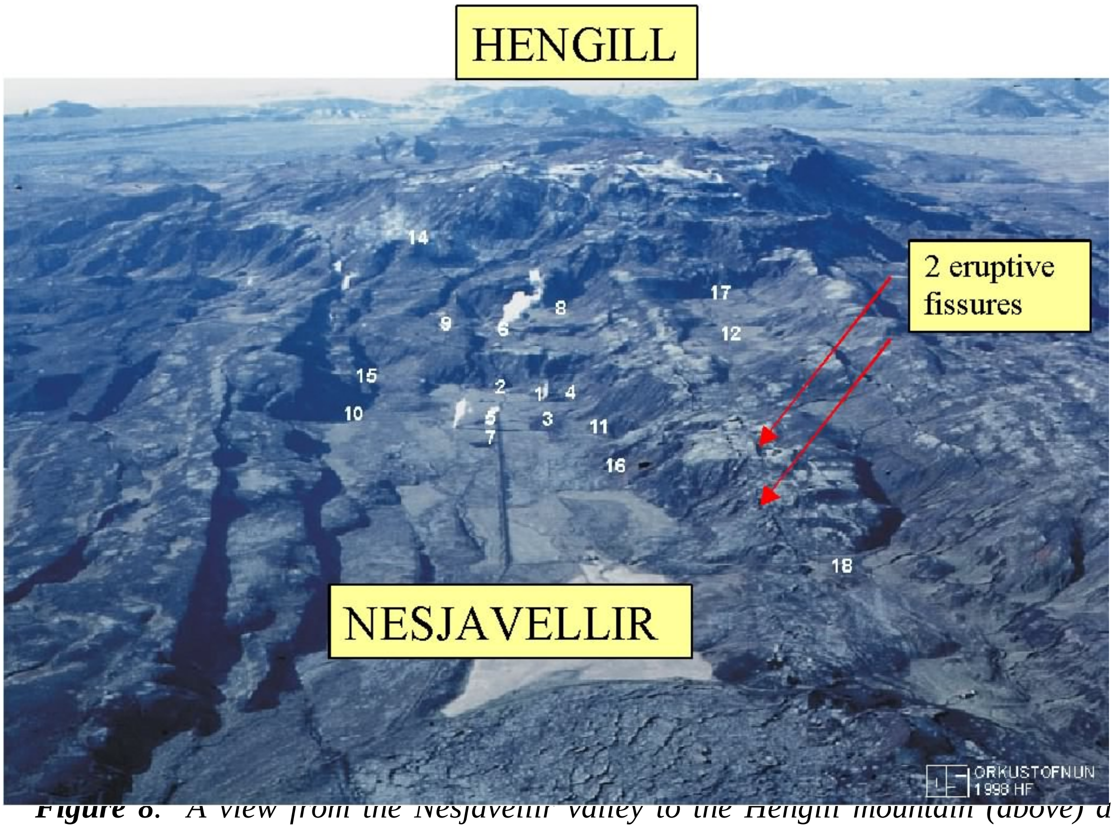

Figure 8. A view from the Nesjavellir valley to the Hengill mountain (above) and further to the south to Hellisheidi. White numbers indicate drillholes. Two Holocene volcanic fissures cross the drillfield on the right hand side, the older one 5500 year old, the younger about 2000 year old. These eruptive fissures and parallel faults control up- and outflow of hot water and steam from the center of the Hengill system.

The Nesjavellir Geothermal Field is located just north-east of the Hengill mountain (Figures 7 and 8). The existence of a high temperature (>380°C) below 2 km depth in well NJ-11 suggests proximity to a magmatic heat source. The center of magmatic activity is to the south of the wellfield. Tectonic activity is episodic and accompanied by rifting and major faulting along the fissure swarm that intersects the central volcano as magma is injected into the fissure swarm. Major rifting has taken place after the last eruption about 2000 years ago indicating magmatic activity at depth within the fissure swarm. Thus the primary heat source for Nesjavellir is probably partially molten rocks beneath the central volcano causing a major upflow of geothermal fluids. On the other hand the upper crustal intrusions found within the

Nesjavellir system itself are secondary heat sources suggested by thermal cracking at 2-6 km depth observed in analysis of microseismicity (Foulger 1984). The anomalously high temperature in well NJ-11 is probably related to a recent intrusive event. The intrusions also enhance the permeability of the reservoir (Steingrímsson et al. 1990). The Nesjavellir field has been harnessed, and presently the geothermal energy is used for space heating (200 MWt) and for production of electricity for the national grid (90 MWe). The field was developed from 1965 to 1990, and production started in 1990, and has been increased in steps.

***Figure 9**. The Nesjavellir power plant was built just east of wells no.11 and 16 (photo by Emil Þór)*

To date a total of 22 deep geothermal wells have been drilled Nesjavellir, 14 of these are used for the present production. The average output is 90 MWe (Steingrímsson et al., 2000, Gíslason, pers.com.2003). Frequent monitoring of the wells has been carried out, with weekly recording of wellhead pressure and/or water level; and also flow rate and enthalpy measurements and sampling for chemical analysis as well as downhole pressure and temperature measurements at least once per year.

For the last decade a simple conceptual model has been used to describe the Hengill hydrothermal system (Figure 10). The model assumes that the main heat source and upflow zone lies under the Hengill mountain itself. The red arrows indicate flow directions of hot water and steam, and the blue arrows inflow of cold recharge water. During the last 5 years, 4 new wells NJ-19 to NJ-22 have been drilled at Nesjavellir, three of them directional wells towards the south below the Hengill mountain. And since 2001, 5 new wells (four directional) have been drilled in the flat area on the left side (south side) of Figure 10. The wells on the south side added valuable new data to the knowledge of the Hengill hydrothermal system and are discussed further in the next chapter.

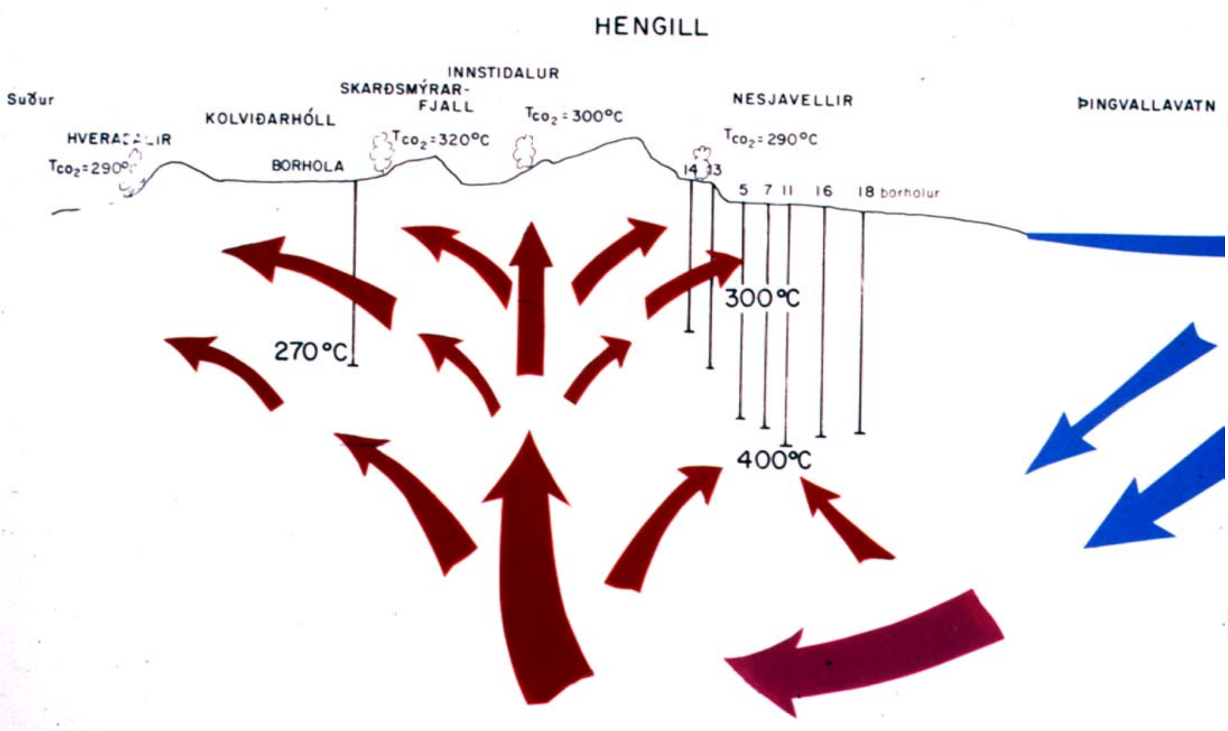

__Figure 10__. A conceptual model of the Hengill hydrothermal system. Several drillholes at Nesjavellir are shown and a single well, drilled in 1985, south of the Hengill mountain. Four new wells (NJ-19 to NJ-22) have been added at Nesjavellir side since 1999, and five new well (HE-1 to HE-5) on the south side since 2001 (flat area near the well from 1985 in the diagram above). See text for discussion

During the feasibility study, it became an additional assignment to look for a suitable drillsite for an IDDP well outside the Nesjavellir field somewhere in the larger Hengill area. The new wells on the south side all show temperature inversion with depth, with the highest temperature about 270°C at 900-1200 m depth, but around 220°C near the bottom at 1600~2000 m. The 270°C fits neatly the model in Figure 10, while blue arrows, indicating cold water recharge from the south, may possibly need to be added to the model. We are still waiting for downhole temperature data from the three wells drilled last summer. The centre of the Hengill system remains to be drilled as well as the main upflow zone.

From the discussion above it should be pretty obvious that discussion on well siting in the Hengill volcanic system of a 5 km deep IDDP well, necessarily needs to focus on the Nesjavellir part of the geothermal system. The centre of the upflow zone might still be considered as a target for deep drilling, but hardly justified without a single drillhole to support such siting.

2.3 Krafla

The Krafla high temperature geothermal system is located within the Krafla caldera in North-eastern Iceland (Figures 2 and 11). The geology of the area is dominated by an active central volcano including the caldera and an active cross cutting fissure swarm. The volcanic activity at Krafla is episodic, occurring every 250-1000 years, each episode apparently lasting 10-20 years, judging from the last volcanic episode. The last eruptive episode lasted from 1975-1984, resulting in 21 tectonic events, and 9 volcanic eruptions. A magma chamber (Figure 12), evidently the heat source for the geothermal system, was identified from S-wave attenuation at 3-8 km depth during the 1975-1984 volcanic activity (Einarsson 1978).

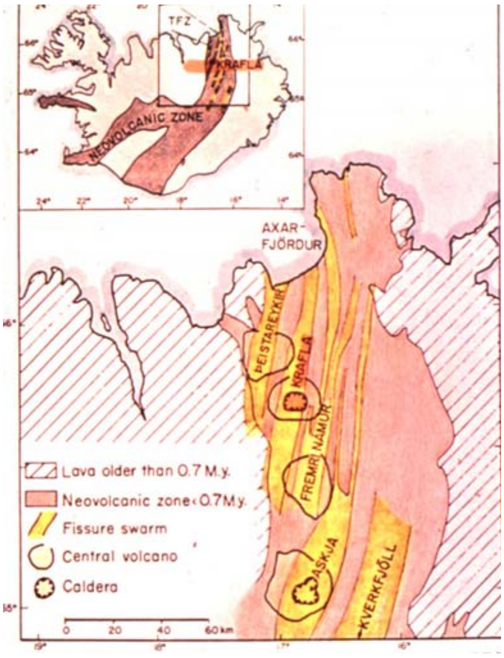

Figure 11. *A map showing the location of 5 central volcanoes in the NE-Iceland volcanic rift zone. En echelon arranged fissure swarms, several tens of km long, are linked to all the volcanic centers. (see also simplified geological map in figure 2).*

Figure 12 shows a schematic view of the magma chamber, detected in 1978. A solidifying magma chamber under the Krafla well field is a sufficiently reliable hypothesis for the purpose of well siting for IDDP, and in line with accumulated well field data on gas emission and temperature distribution. In Figure 12 some of the key elements of the Krafla high temperature field are shown (see also the figure caption). The most important one with respect to IDDP is the Hveragil explosive fissure, which serves as one of the main hydrothermal upflow zones, and inevitably becomes one of the most attractive targets for an IDDP well.

The oldest exposed rocks in the Krafla central volcano are hyaloclastites from the 2nd last glacial (younger than 200.000 years. At the end of the last interglacial, about 100.000 years ago a huge (some km^3), explosive acid eruption resulted in the formation of the Krafla caldera, which is 8 by 10 km in diameter (outlines in Figure 13). During the last glacial the caldera was more or less filled with volcanics simultaneously with widening of the fissure swarm

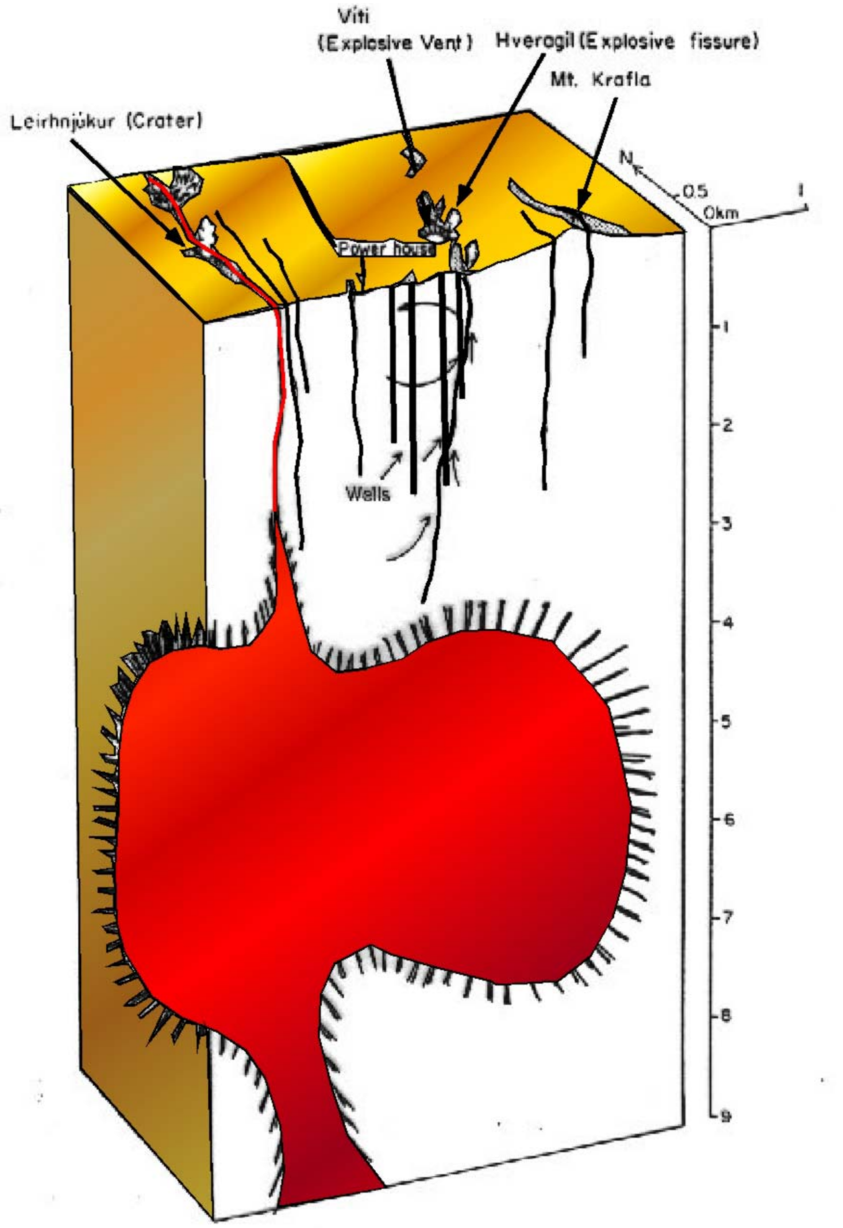

Figure 12. A conceptual model of the Krafla magma chamber showing most of the key elements discussed in the context of siting an IDDP well. Namely the heat source itself; the Hveragil explosive fissure which is the main hydrothermal upflow zone of the Krafla high-T field; the Víti explosive vent from the beginning of the 1724-1741 volcanic episode, and the Leirhnjúkur crater row which erupted 9 times during the Krafla fires 1975-1984, and several times during the Myvatn fires (1724-1729, 1741) and earlier volcanic episodes.

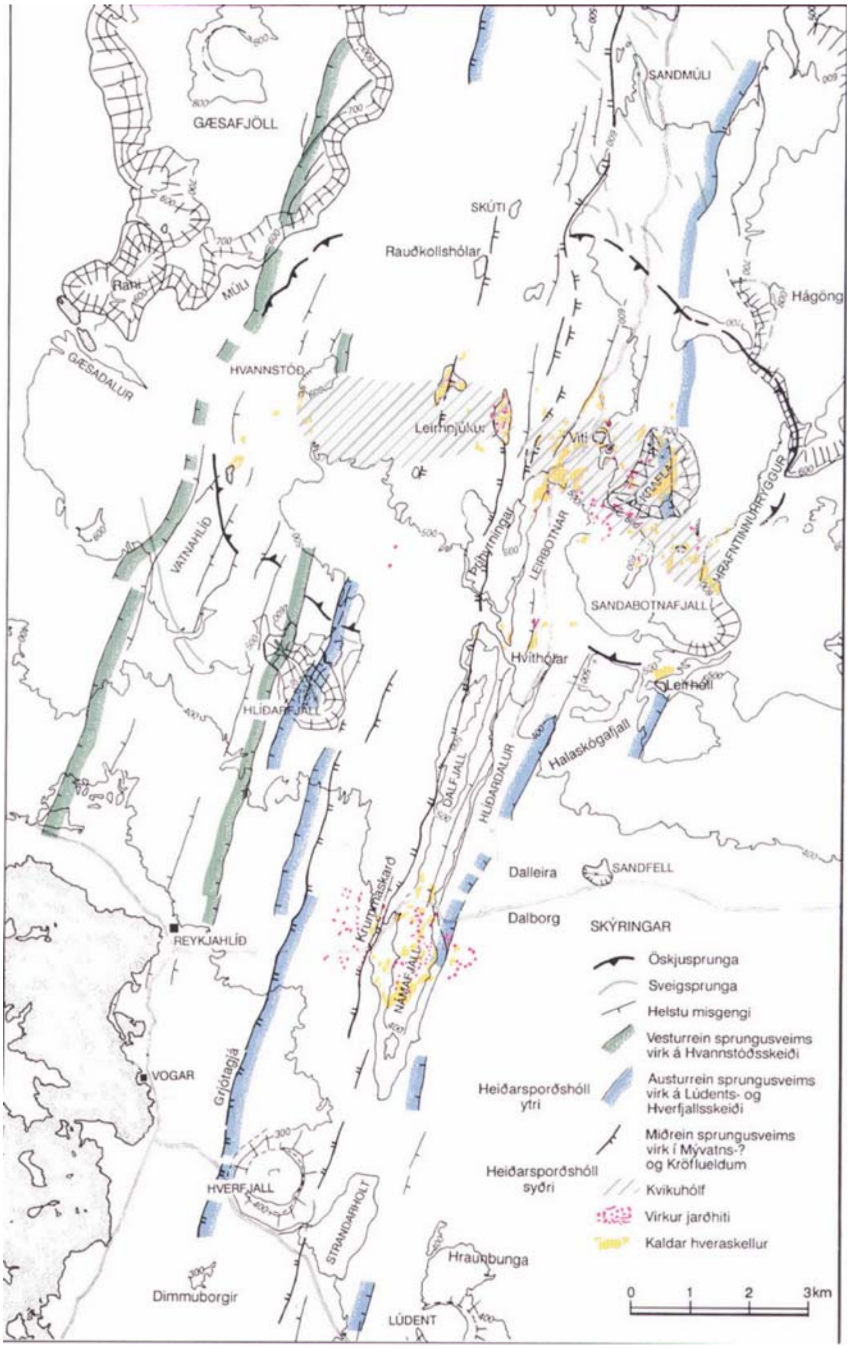

Figure 13. *A simplified structural map (from Saemundsson 1991) showing the presently active fissure swarm,for the last ~3000 years, and also more than 8000 years ago (outlined in blue), and a fissure swarm further west, active during mid-Holocene (outlined in green). The caldera fracture (solid black dash, chief faults and fractures (lighter dashes), center of Mývatn and Krafla fires (double marked dash), outlines of the magma chamber (inclined hatch), active fumaroles (red symbols), hydrothermal surface manifestations (yellow symbols).*

crossing the center, by some tenths of meters every 10 thousand years, and subsidence of the order of 100 m for the same time interval, resulting in the elliptical shape of the caldera

(Saemundsson, 1991). During Holocene, extensive volcanic activity has taken place within the caldera, especially within the presently active fissure swarm (see Fig. 13), characterized by fissure eruptions and lava flows outside the hydrothermal fields, and explosive activity within the hydrothermal fields. Hveragil for instance, an explosive crater row and the main hydrothermal upflow zone, may have been formed during late Glacial but was reactivated by explosive activity in early Holocene. The explosive crater Víti, the most spectacular one in the area was formed in 1724 at the beginning of the Mývatn fires, and is the youngest eruptive formation within the Krafla drillfield. The second youngest eruptive product within the drill field is a crater row and lava from Daleldar, about 1100 years old. The Krafla power plant was built on top of this crater row and its lava. The 3d youngest eruptive products close to or within the drill field, relate to Holseldar, about 2000 year old. Explosive activity took place just northwest of Víti in Holseldar, and a fissure eruption took place on Sandabotnafjall and on the northeastern slope of the Krafla mountain, with lava flows at both sites. This 2000 year old eruption almost cut through the easternmost part of the Krafla drillfield where well KJ-18 is located, a 2200 m deep well considered a “well of opportunity” in IDDP.

Surface hydrothermal manifestations extend over an area of about 15 km^2 (Figure 13). Based on surface activity and properties of well fluids at least four sub-fields, Leirhnjúkur, Leirbotnar, Suðurhlíðar and Hvíthólar have been identified. Leirhnjúkur and Leirbotnar were affected by magmatic gas during the volcanic activity 1975-1984. Leirhnjúkur has never been drilled but the other three have. In fact drilling was moved from Leirbotnar to Suðurhlíðar and later Hvíthólar because no signs of magmatic gas were found in fumarole fluids from the latter two. In subsequent chapters, the well fields will be discussed in closer detail, but this overview is concluded by showing the characteristic temperature distribution within each of these three subfields. The Suðurhlíðar field is the hottest, following the BPD-curve from the surface down, and identical to Leirbotnar field from 1200 m down, the bottom hole T~340-350°C.

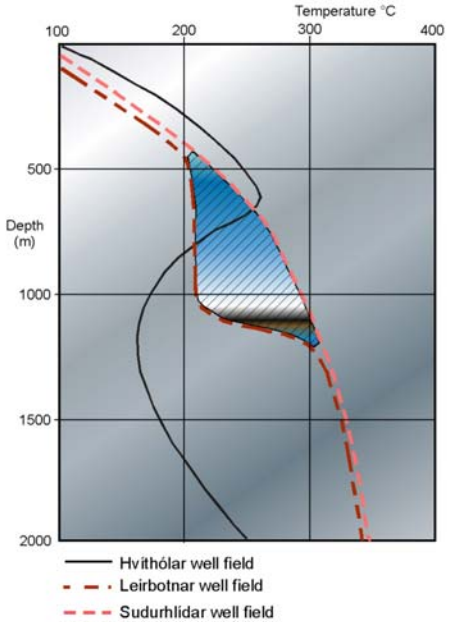

Figure 14. *Characteristic temperature distribution within the three drill fields in Krafla, Suðurhlíðar, Leirbotnar and Hvíthólar***.**

3 GEOLOGY

3.1 Geology of the Reykjanes Field

An overview of the Reykjanes peninsula was discussed in Chapter 2. In Figure 15 there is a birds eye view over the tip of the peninsula, the Reykjanes itself. Steam from the Eldvörp and Svartsengi high temperature fields can be seen in the distance.

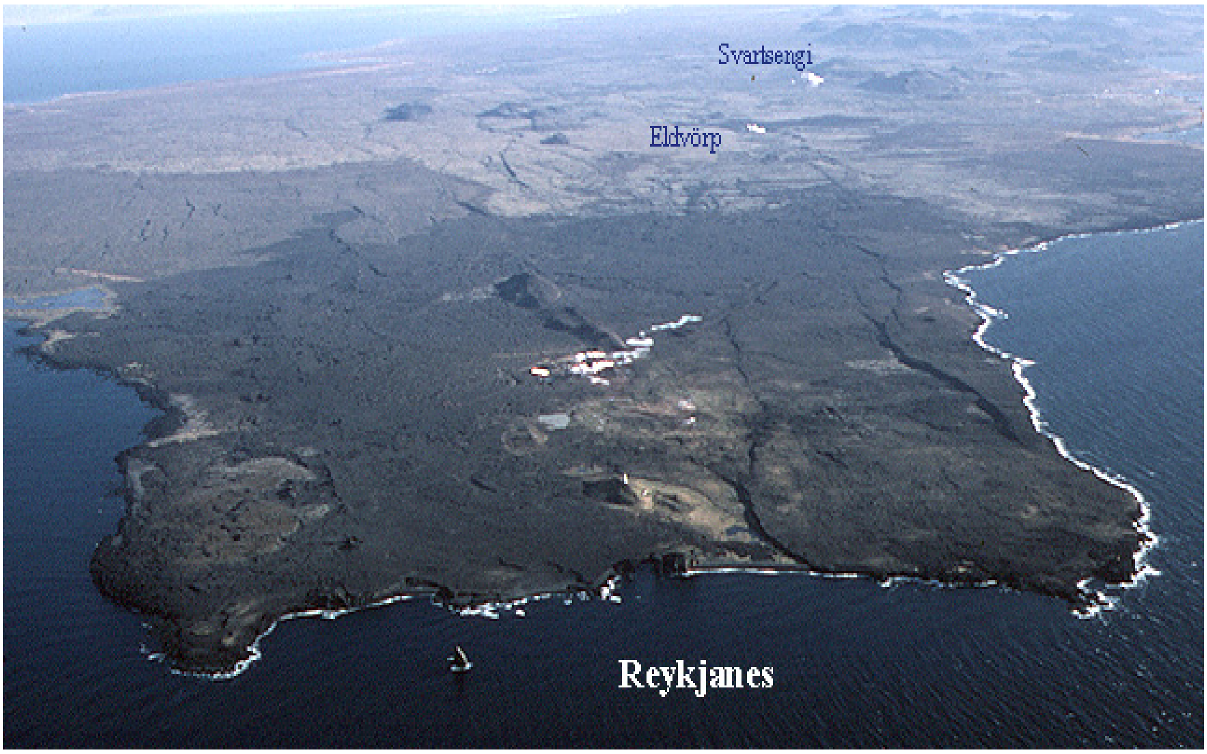

Figure 15. *View over the high temperature field at Reykjanes, the landward continuation of the Reykjanes Ridge. The surface manifestations of the Reykjanes high-temperature field are in the central part of the fissure swarm. Most of Reykjanes is covered by Holocene lavas while the tops of submerged hyaloclastite ridges poke the lava fields.*

A geological map of Reykjanes is shown in Figure 16. The distribution of the Holocene lavas is pretty simple, the early-Holocene eruptive crater rows and lavas mostly occurring on the SE-side of Reykjanes, and have since been faulted and fractured during later tectonic events. The older lavas are partly buried by late-Holocene lavas in the SW part of the area, and so are evidently all earlier faults and fractures. At least four volcanic eruptions have taken place along the young Stampar crater row in late Holocene times, the latest one in 1226 AD. The more extensive Eldvörp fissure eruption took place the same year as seen in Figure 3, which shows the distribution of all historic (younger than 874 AD) volcanic eruptions on the

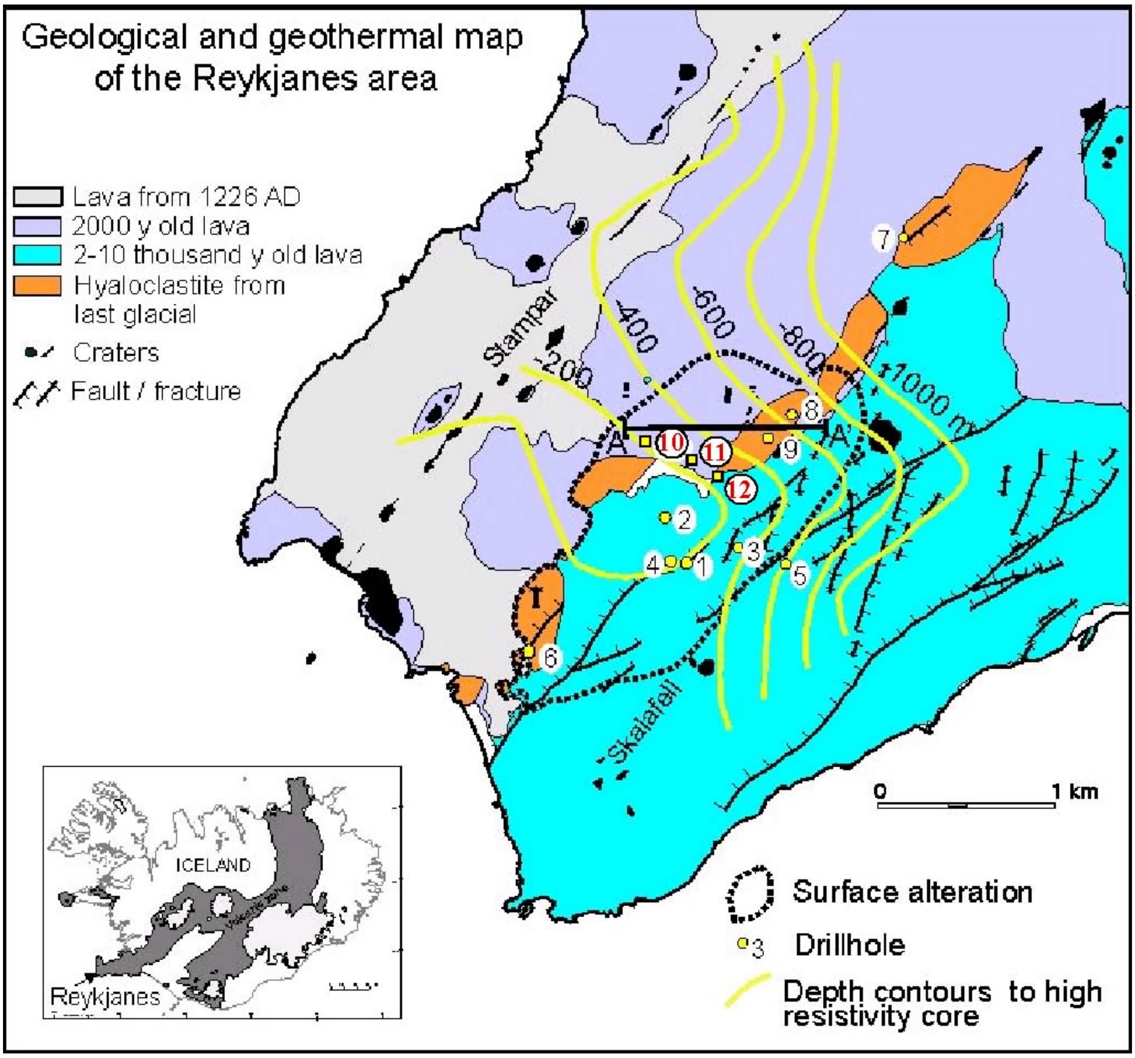

Figure 16. *A geological map of Reykjanes showing the age distribution of lavas, crater rows, main faults and fractures, hydrothermal surface alteration, depth contours to a high resistivity core, and locations of drillholes. The latest wells No. 10, 11, and 12 (red numbers) where drilled in 1999, 2001 and 2002 respectively. Well No. 12 is the deepest high temperature well in Iceland, 2500 m deep.*

peninsula. The volcanic dikes accumulating at depths in general act as heat sources for the geothermal systems and retain vertical permeability. Gudmundsson (1986) modelled four magma reservoir under the "string" of high temperature geothermal fields from Reykjanes inland, and concluded these magma reservoirs covered an area of 372 km^2, and suggested a 6-7 km depth to the top of a magma reservoir under Reykjanes. Results of the seismic study presented in Chapter 7, do not confirm this, but suggest a 6 km depth to the brittle/plastic boundary (at ~700°C) under Reykjanes, and no magma chamber (see Chapter 7).

The Reykjanes hydrothermal field onland is relatively small, perhaps ~3x3 km. Resisitivity surveys suggest that the geothermal area is somewhat larger (see Chapter 5), but an offshore resitivity survey is needed to find out the extent of the geothermal system below the seafloor. The relatively small size of Reykjanes limits the options for an IDDP drill site. So far we have suggested the Stampar eruptive fissure as an ideal and promising target (Fridleifsson and Albertsson 2000), but the center of the drillfield may possibly be just as good. Since 1999, three new deep drillholes have been drilled, No. 10, 11 and 12, in the center of the drillfield (see Figure 16). Well No. 12 was drilled to 2500 m depth last autumn, and is presently the deepest high-T well in Iceland. It is cased by 13 3/8” cemented production casing to about 800 m depth, and was drilled by a 12 ¼” tricone bit with a downhole motor in record time. The well is barefoot, and could, depending on a number of political and policy decisions, be deepened to 4-5 km in one or two steps and become a “well of opportunity” or a full scale IDDP well. The same applies to well No. 11 which has the same construction and is 2248 m deep. In both cases, a 10 3/4” casing would need to be installed and cemented prior to deepening by coring or rotary drilling.

The plan at Reykjanes has already been accepted by the authorities after environmental assessment, both for deepening the wells discussed above, and for a deep drillhole within the Stampar eruptive fissure. A near future plan by the Hitaveita Sudurnesja company is to drill a step-out well in the Stampar fissure zone. Of course, it would be desirable to wait for new information on all the drillsites in order to compare them with respect to temperatures and permeability at 2000-2500 m depth before siting and drilling the first IDDP well in the field.

The reader may feel that a conclusion on siting an IDDP well has already been reached without a presenting more detailed description of the Reykjanes system. Figure 16 shows the location of all drillholes at Reykjanes. Only wells No. 9, 10, 11 and 12 are in operation, all others have been abandoned, either cemented or are used for monitoring purposes. The fact that all the three new wells experienced large circulation losses (feed points) at great depth, close to or below 2 km depth and near 300°C, is perhaps one of their most interesting aspects. No evidence excludes the possibility that deeper aquifers will be met by deeper drilling. Considering the small surface area of the Reykjanes system as a whole, in addition to environmental restrictions on surface access to the southwestern part of the field, a detailed knowledge of the extent of a deep seated workable reservoir is of fundamental importance to the energy company.

The chemical character of the deep aquifers in wells 10, 11 and 12 remains to be studied, and full knowledge of the temperature distribution is not yet available. The reason for the delay relates to mechanical failures in both well 10 and 11. Apparently, a differential thermal expansion of the two uppermost casing rods caused a leaky joint. The problem area is accessible from the surface and repair will be completed within the next few months. In addition to this, the slotted liner in well No.10 seems to be damaged at about 1100 m depth, possibly because of upflow of corrosive fluid from the lower aquifer into an upper aquifer at 1100 m. The incident has not been fully explained as yet, delayed by the repair of the leaky joint. No slotted liners were inserted into wells No.11 and No.12. That makes them easily accessible to IDDP, yet depending on a number of decisions, but both wells fulfil the width- and depth requirement for a proper IDDP well of type B (see part II of the feasibility report). Later this year we expect to have fuller knowledge of the fluid composition, temperature distribution and the deep reservoir properties in the vicinity of well No.12.

Referring to the modeltrack shown in the foreword of this report, and shown again next to Figure 17, there are indications from the deep temperature in well RN-10, that the bottom of the convection cell has not yet been reached. The same may apply to the deeper wells No. 11 and 12, which haven’t recovered from drilling, but downhole logging is anticipated with considerable interest. So far the data, however, seems to indicate a deep convection cell, a positive sign for the possible presence of a deep reservoir, and probably a solid enough reason for pilot coring to greater depths within well No.12 for instance.

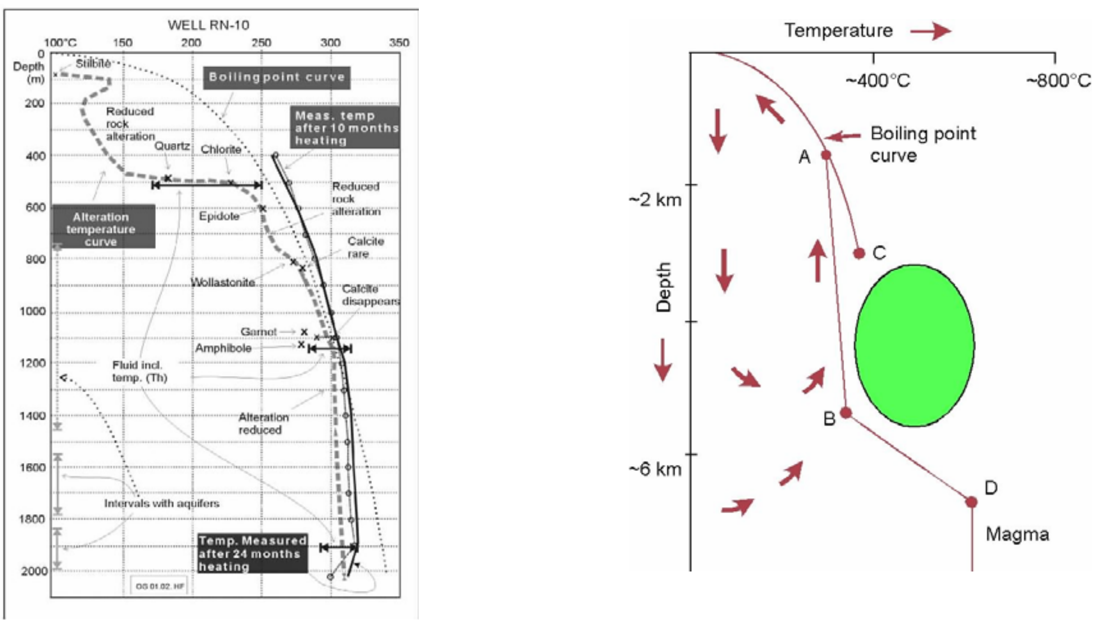

***Figure 17**. Measured temperature and alteration temperature compared with the BPD- curve. The simplified model on the right hand side on a deep convection cell, may apply to the Reykjanes system within the upflow zone. Temperature logging of wells RN-11 andRN-12 are awaited.*

The data accumulated on the subsurface geology, alteration zonal distribution and the alteration history all comes from drill cutting studies. As drill cores are hardly ever collected in Icelandic high temperature wells, experience in drill cutting analysis has accumulated for decades. Figure 18 shows a simplified geological and alteration profile for well RN-10. The gray symbol on the geological column indicates lava piles, and/or pillow lavas, while the green symbol indicates hyaloclastite formation. The yellow symbol indicates sedimentary succession. Interestingly, these sediments include remains of shallow marine molluscs, implying both that the Reykjanes peninsula was built up from the sea floor, and that the degree of subsidence in Pleistocene time has been considerable, of the order of some hundreds of meters.

The strata in well No. 10 range from basaltic lava formations (possibly pillow basalt formations to some extent) and intrusives at the deepest level, to shallower tuffaceous volcanic successions intercalated with reworked shallow marine fossil-rich sediments between 1000 - 500 m, and lastly hyaloclastites, pillow basalt and subaerial lavas. The formations are relatively high-porosity and low permeability, and the aquifers encountered (black triangles in Fig. 17) in the well are largely related to fractures along sub-vertical dyke intrusions. The largest aquifer (1930-1960 m) near the bottom is related to a sub-vertical fracture, rich in wollastonite. Intrusive intensity in well No.10 is relatively low (~ 5 %). A provisional figure for intrusive intensity in wells No.11 and No.12 is about 19 %, in both cases. In well No.11, below 1 km depth, the intrusive intensity is only about 15 %, but about 28 % below 1 km depth in well No.12. Compared to both Nesjavellir and Krafla, these figures for intrusive intensity are remarkably low, but reflect the immaturity of the young Reykjanes system pretty neatly.

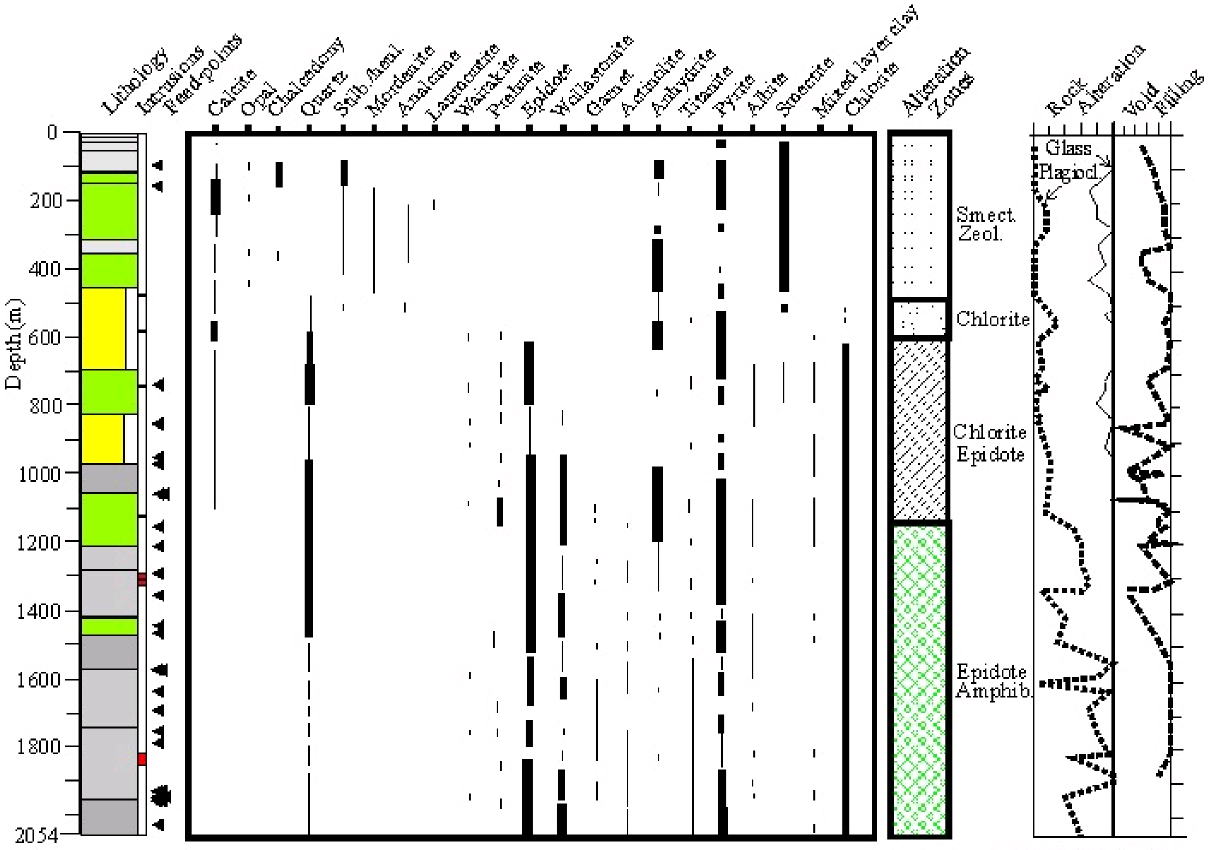

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Figure 18. Distribution of alteration minerals, alteration zones, glass and plagioclase alteration and degree of void filling in well RN-10 (from Franzson et al. 2002).

The distribution of hydrothermal alteration minerals in Figure 18 shows that the well entered the high-temperature system below about 500 m depth. From there a progressive alteration zonation occurs, ranging from smectite-zeolite to > chlorite > chlorite-epidote > epidote-actinolite zone. The sequence of mineral deposition in rock cavities indicates that the geothermal system has from its initial stage been progressively heating up. The highest bottom temperature measured to date is about 320°C. Due to a damaged liner or some obstruction near 1100 m, temperature monitoring in RN-10 has not been possible below that depth for some time. Even so, the bottom hole temperatures are not likely to change significantly. Measurements of T_h in fluid inclusions show a good correlation with alteration and measured formation temperatures, while T_m-measurements show a wide range in salinity, irrespective of depth, from freshwater to seawater compositions, the latter being close to the present salinity of the field. Evidence suggests that well RN-10 is sited further away from an upflow zone than RN-9, while temperatures in well RN-10 below 1 km depth are up to 20°C higher than found elsewhere in the reservoir, reaching a maximum of about 320°C.

Figure 19 shows that the alteration zones between wells 10 and 9 are pretty flat lying, while the temperature profile seems to indicate an upflow zone closer to the latter. In the last two years wells RN-11 to 2300 m and well RN-12 to 2500 m have been added. A more detailed model of the Reykjanes system including these wells is likely to appear within this year or next.

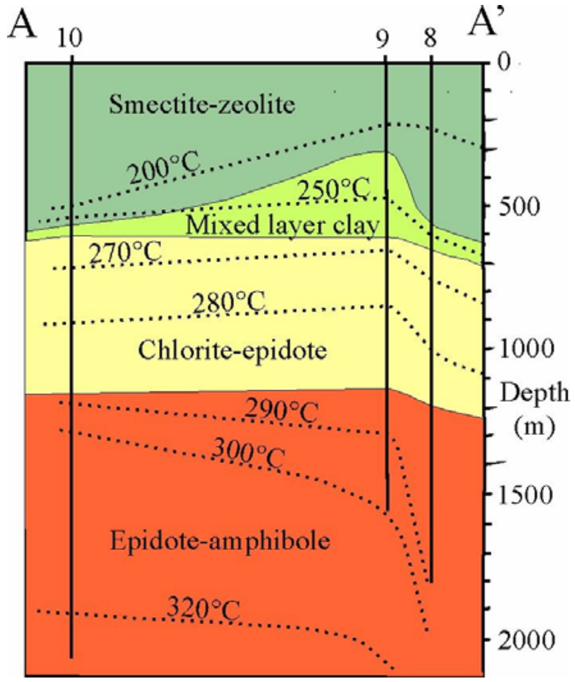


Figure 19*. Cross section A-A' (see fig. 16) between well No.10 to 9 and 8, showing mineral zonation and temperature distribution.*

From the geological data accumulated so far, the intrusive rock intensity between 1-2 km depth is quite low, ~5-30 %, compared to the more mature high temperature systems at Nesjavellir and Krafla, where the intrusive rock intensity within the volcanic centers is some tens of percentages higher. As will be seen in a later chapter and is mentioned above, no real magma chamber has been detected below Reykjanes. From that and the low intrusive rock intensity in the uppermost 2,5 km, which partly relates to near vertical dikes extending towards the surface from depths, a feasible model for the high temperature heat source is that of a simple ophiolitic sheeted dike complex, simplified in Figure 20. A gradual increase of dikes should be the case with increasing depth. From the discussion in Chapter 6, the depth of the seawater recharge zone might be some 6 km at Reykjanes and the bottom of the crust some 5-10 km deeper.

An attempt to prioritize the potential drill sites at Reykjanes is shown in Table 2. The Stampar site has never been drilled so a selection between the two sites is premature and not very meaningful. A full scale drillhole to 2500 m, ready to be cased, evidently beats the cost estimate compared to an undrilled well by a factor of two. Rating of permeability is both qualitative, relative to each other, and evidently speculative. Environmental sensitivity is higher at Stampar that at RN-12, which is in the center of the drill field. The climatic conditions are better at Reykjanes than at both Nesjavellir and Krafla; vary during winter from year to year, but are normally fair for 11-12 months.

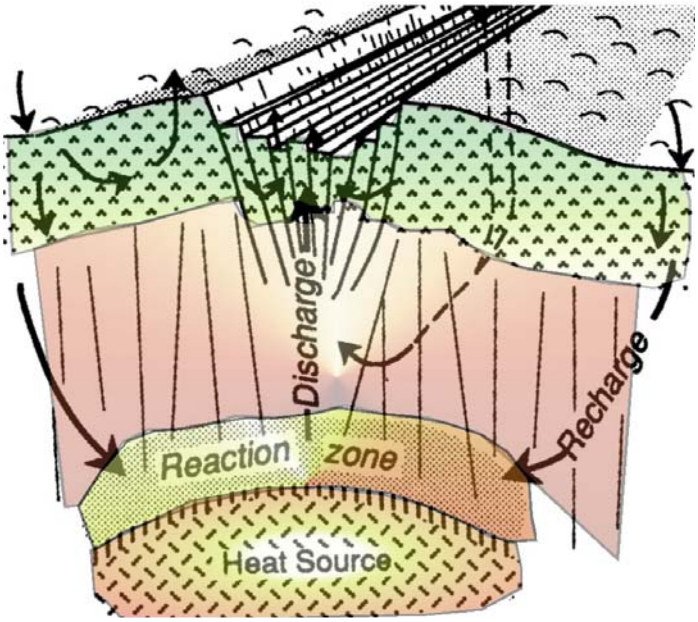


***Figure 20**. A simple ophiolite model seems to apply to Reykjanes. Updoming of the heat source below the high-temperature hydrothermal fields on the Reykjanes peninsula is likely to be the case. Higher intensity of sheeted dikes seems to be a more likely scenario than a cooling gabbro judging from the deep geophysical studies.*

***Table 1.** Priority list of potential IDDP drillsites at Reykjanes*

Drillsite	**Priority**	**Temperature**	**Permeability**	**Environ./geography/climate**
RN-12	**1**	High	High	Already 2500 m deep/no liner
Stampar	**2**	High	High	Adequate – and a stepout
RN-11	**3**	High	High	Already 2300 m deep with liner
Center elsewhere	**4**	High	High	Adequate

3.2 Geology of the Nesjavellir field

The locations of all drillholes in Nesjavellir are shown in Figure 21. Also shown are the two eruptive fissures along the eastern margin of Kyrdalur. The older eruptive fissure, 5500 year old, is just west of and partly buried by the younger eruptive fissure since 2000 years ago. These eruptive fissures and a fault just east of them act as the main conduit for hydrothermal fluid flow up and outwards from the Hengill center. The deepest well at Nesjavellir, NJ-11, 2265 m deep drilled in 1985, was apparently drilled straight into this conduit and interfered with a supercritical hydrous fluid temperature higher than 380°C. The well was sealed by a gravel pack up to about 1600 m, but remained one of the better producers from an aquifer at 1100 m.

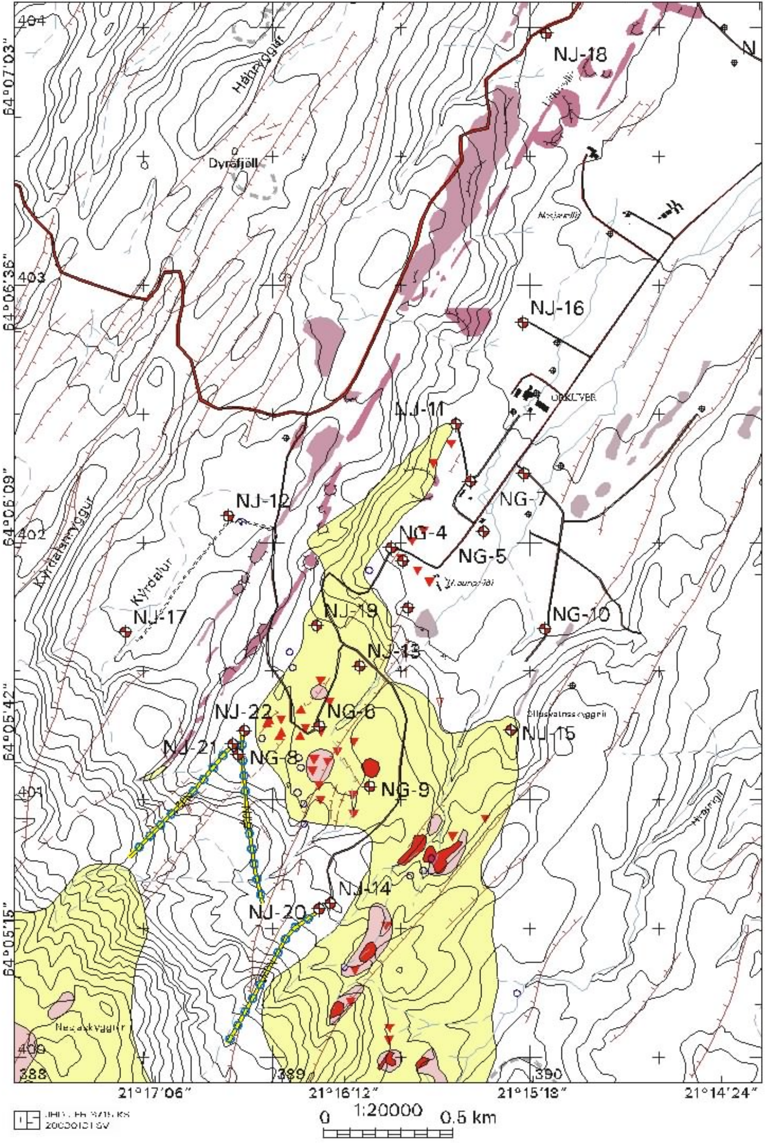


Figure 21. Location of drillholes at Nesjavellir. Yellow areas delineate extinct hydrothermal manifestations, pink and red areas, warm and hot surface activity and red triangles signify fumaroles. Trajectories for inclined wells are also shown.

During drilling completion of well NJ-11 at Nesjavellir (Steingrímsson et al. 1990), a kind of subsurface blowout occurred, where the fluid from the lower >380°C aquifer flowed upwards to meet some 45-60 l/s cold circulation fluid pumped from the surface, both disappearing into a feed zone between 1100-1200 m depth. The pumping of cold water was maintained for some 5 days in an attempt to control the well, but without success. Figure 22 shows the temperature-depth logs from the well during this course of events, with the BPD-curve shown for comparison. Below 2,2 km depth the temperatures exceeded 380^{o} C, but only the lower limit is known as the thermometer could not record higher temperatures. A 600-700 m gravel pack was used to seal off the lower zone. Since, no attempts have been made to re-enter the superhot zone below 2,2 km depth at and near well No.11, a re-entry’s is evidently of key interest to IDDP.

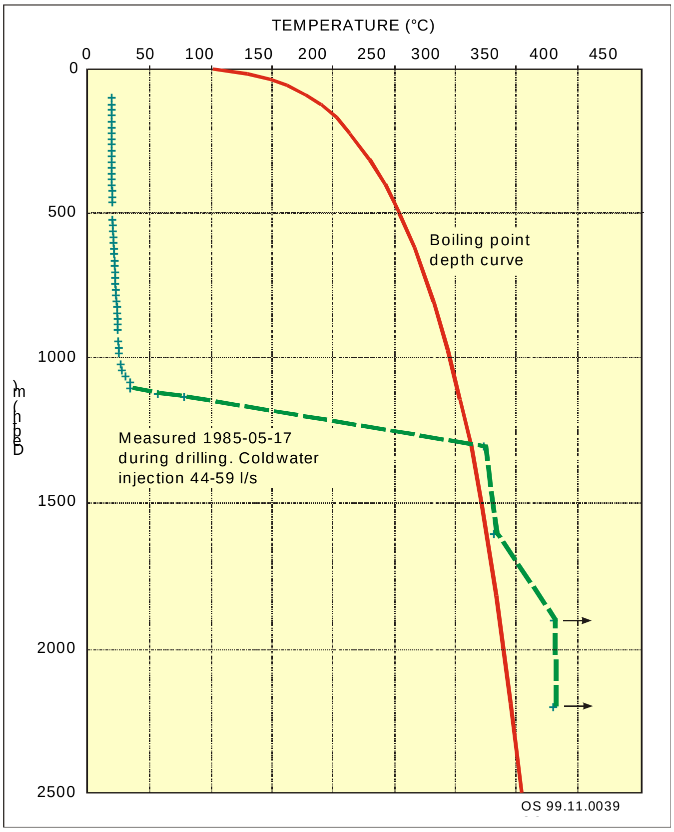


Figure 22. *Temperature - depth curve for the well NJ-11, measured during drilling. The BPD-curve for pure water is shown for comparison.*

A simplified lithological cross-section through the Nesjavellir field is shown in Figure 23. The base of the Hengill volcanics is set at some 300.000 years, below which depth subglacially formed hyaloclastites become less abundant, but subaerial lava flows more so, forming several discrete series. Also shown are all the main faults detected within the field. Some of the faults reach the surface, while others are buried and inferred from drillcutting data by comparing lithological sections between wells. Wells No.17 and No.12 are furthest to the west in the Kýrdalur valley, whose elevation is about 150 m higher elevation than that of the Nesjavellir valley. The additional pressure head of 10-15 bar, makes Kýrdalur a favourable drillsite to attempt to re-enter the superhot zone NJ-11 encountered. Well No.12 was listed as one of the options to considder as a “well of opportunity” during IDDP/ICDP workshop 2. It coincides with one of the most favourable sites for a full scale IDDP well, as will be discussed below.

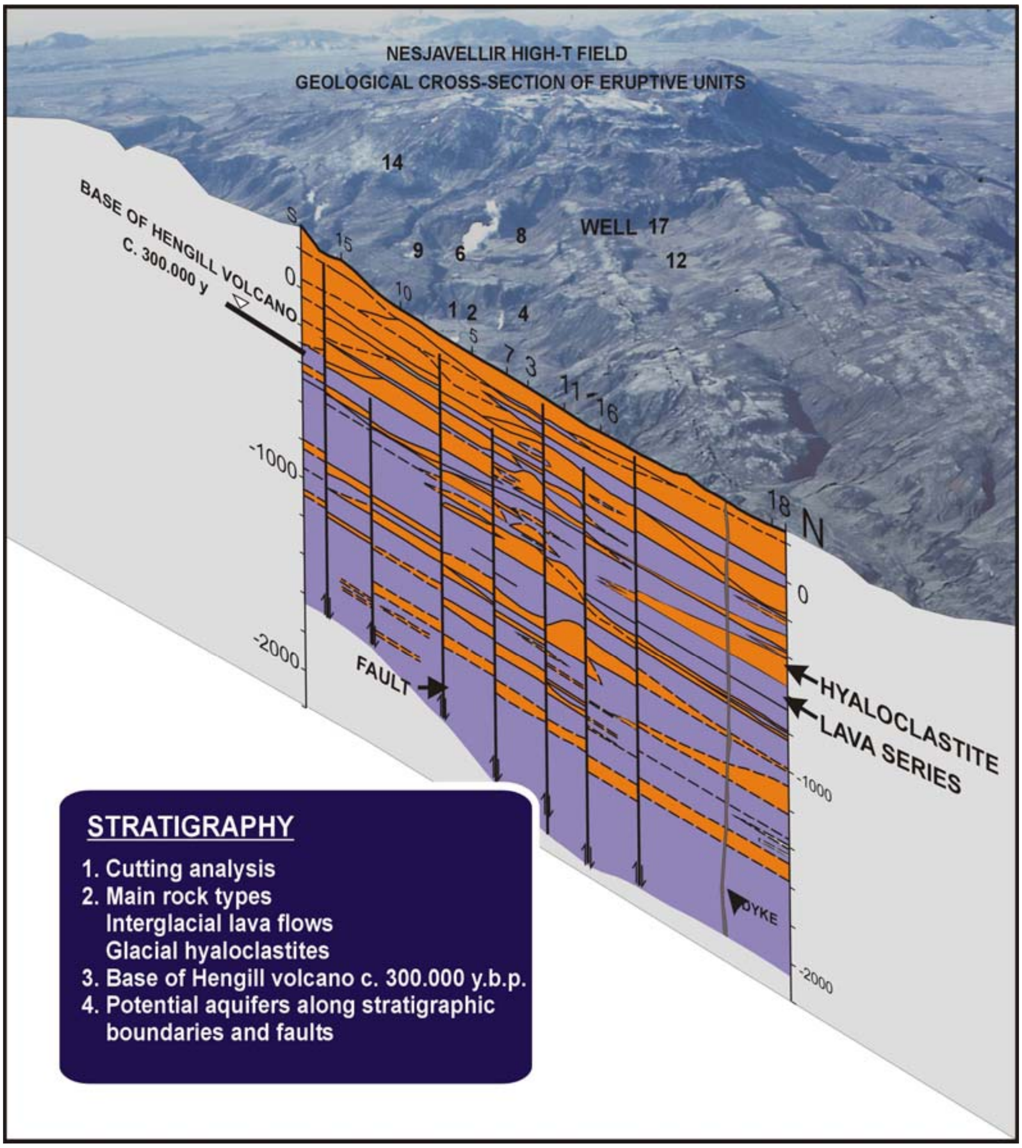


***Figure 23**. Simplified geologcial cross-section through the Nesjavellir drill field (from Franzson, 1998)*

In Figure 24 a schematic presentation of the intrusive rock intensity in Nesjavellir is shown along the same cross section as in Figure 23. Three intrusive rock types are distinguished as altered basalt intrusion, intermediate to acid diorite dikes, and relatively fresh (and young) basaltic dikes. The intrusive rock intensity, based on drill cutting analysis, is quite low in the uppermost 1000-1200 m, but increases drastically to some 40-60 % in the next 300-400 m, below which depth 60-100 % of the drillhole cuttings are composed of intrusive rocks. The intrusive complex, is apparently composed of low angle sheeted dikes, dipping towards the Hengill mountain in the south. The youngest dikes, reaching towards the surface, are rarely intersected by drillholes, suggesting they are pretty close to vertical, in the depth range

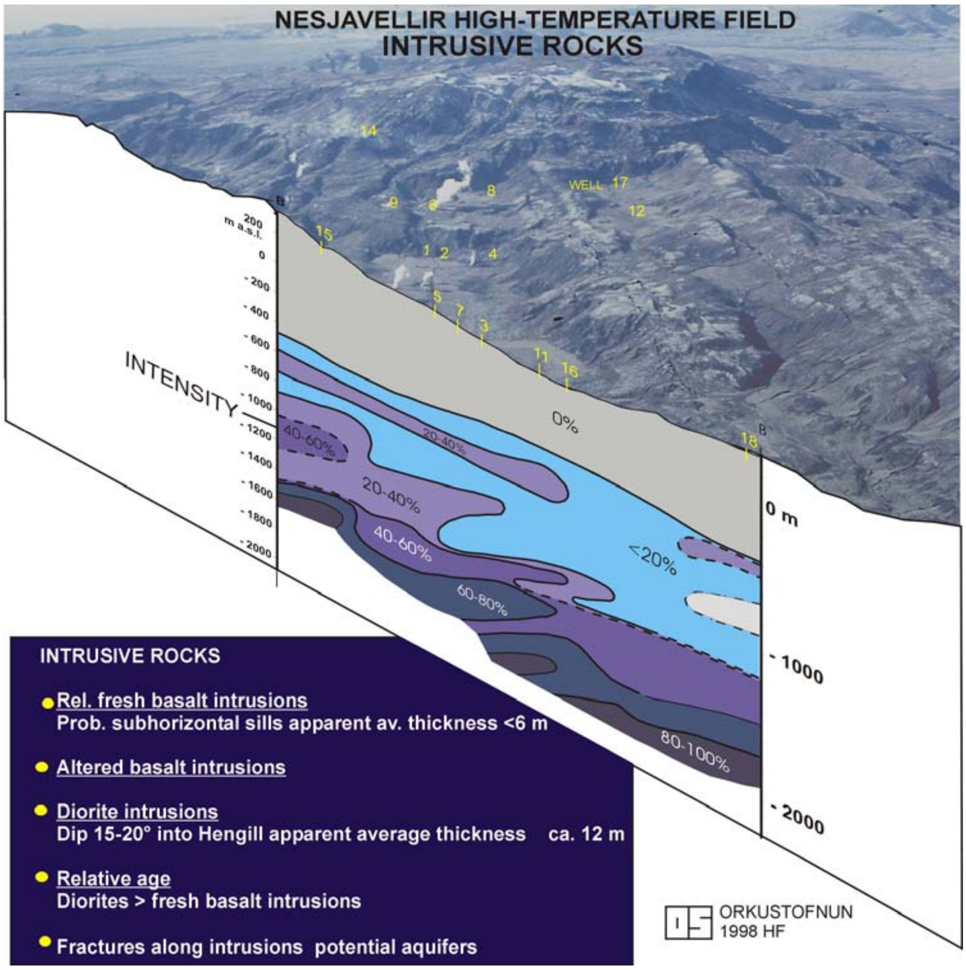
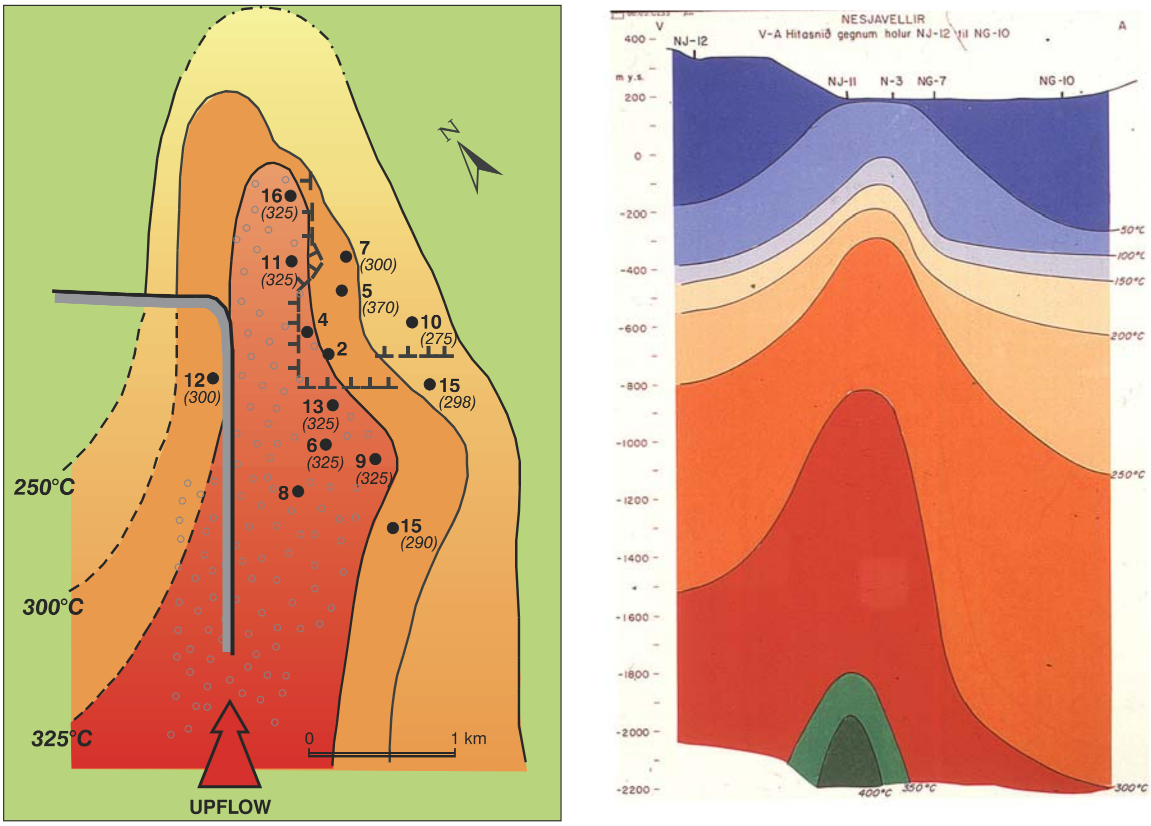


Figure 24. *Schematic representation of intrusive rock intensity along the same section as in fig 23.*

drilled. Moving deeper, the dikes might possibly bend inwards to the graben center in a listric fashion, as faults and fractures are known to behave in similar tectonic settings. Within the crustal depth of interest to IDDP, some 4 -5 km, the eruptive dikes are not likely to bend at all significantly (K. Saemundsson, 2002, pers.com) and should be assumed to be subvertical. This may relate to a relatively slow spreading rate in Iceland, as compared to fast spreading oceanic ridges where listric faults at shallow depths have been observed (P.Pezard, 2002, pers.com).

A map showing the temperature distribution of the Nesjavellir system at about 600 m depth is shown in Figure 25 a), and in Figure 25 b) a W-E cross-section from well No.12 to well No.10 showing the temperature-depth distribution from Kýrdalur across the Nesjavellir valley, just over 1 km. From Figure 25 it is pretty obvious that the main upflow zone is subparalell to the eruptive fissures of late Holocene age, on the west side of the Nesjavelllir valley. The upflow zone, shown by the 300°C, 350°C and 400°C isotherms in Fig. 25b, is pretty narrow, and with respect to IDDP the shape of the 300°C isotherm is noteworthy.



a) *b)*

Figure 25. ***a)*** *A map showing measured and simulated temperature distribution at 1400 m.b.s.l. at Nesjavellir (~1600 m depth), indicating up- and outflow from the Hengill mountain in the south towards the northeast into Nesjavellir.* ***b)*** *A cross section from well No.12 to well No.10 showing the main upflow zone at Nesjavellir (from Steingrimsson et al. 2000)*

As stated above, the key interest of IDDP is to access the high pressure, high temperature zone at Nesjavellir. Mainly because of the high pressure (P) at shallow depth in the center of the up-flow zone as experienced by well No.11, but also due to environmental and geographical restrictions on the west side of the Nesjavellir valley, siting an IDDP well there is literally out of the question until more is known about the center of the up-flow zone. However, sidetracking by drilling from either side seem quite possible for physical reasons, which mostly hinge on the minimum pressure head attainable within the wellbore at each depth. A cemented safety casing to about 2,4 km is needed to enter P-T at or above the critical point, in order to control the well safely. The 300°C isotherms in Fig. 25b, for instance, give some indication of the likely fluid P on both sides of the up-flow zone. By looking at the temperature distribution in Figure 25, quite a few options for selecting a potential drillsite for an IDDP well appear, only physical conditions accounted for. The Kýrdalur valley on the west side is evidently of top priority, but the eastern side of the Nesjavellir valley may be just as feasible from the physical point of view. In order to simplify the discussion, five options for a potential drill site are shown Table two for Nesjavellir, and two for other parts of the Hengill fields elsewhere. For Nesjavellir, two of the drillsites, are in Kýrdalur, one near well No.12, and the other further to the south near well No. 17. On the east side of drillfield, a drillsite near well No.15 in the south is made an option, and also another site further to the north, near well No.10. In order to prevent misunderstanding, the fifth option is shown as re-drilling of well No.11, which for solid physical reasons is rejected, and therefore ranked as low-priority.

The discussion of geology and borehole physics is concluded here by showing a conceptual model of the Nesjavellir drillfield from Franzson (1998). The potential drillsites mentioned above, and shown in Table 2, can be viewed with reference to this model. The good part is, if a supercritical fluid can be studied and successfully harnessed in one IDDP well, there is plenty of room for many additional super deep production wells within the Nesjavellir drill field. Thus, the drilling of one IDDP well at Nesjavellir might be the beginning of a new era in power production for the capital city, Reykjavik.

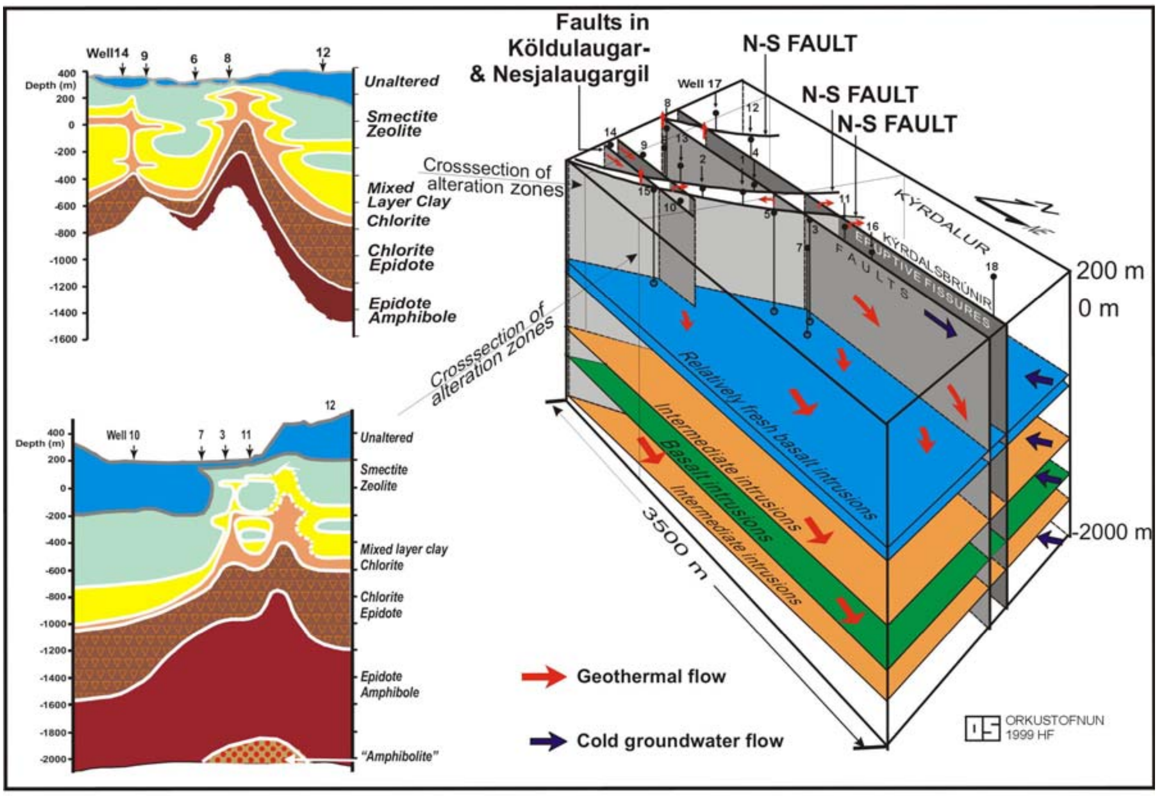


Figure 26*.* *A conceptual model based on drillhole data (Franzson, 2000). The hydrothermal alteration zonation pattern is shown on the left hand side of the diagram. Potential IDDP drillsites are proposed on both the east side of the Nesjavellir valley, and in Kyrdalur furthest to the west.*

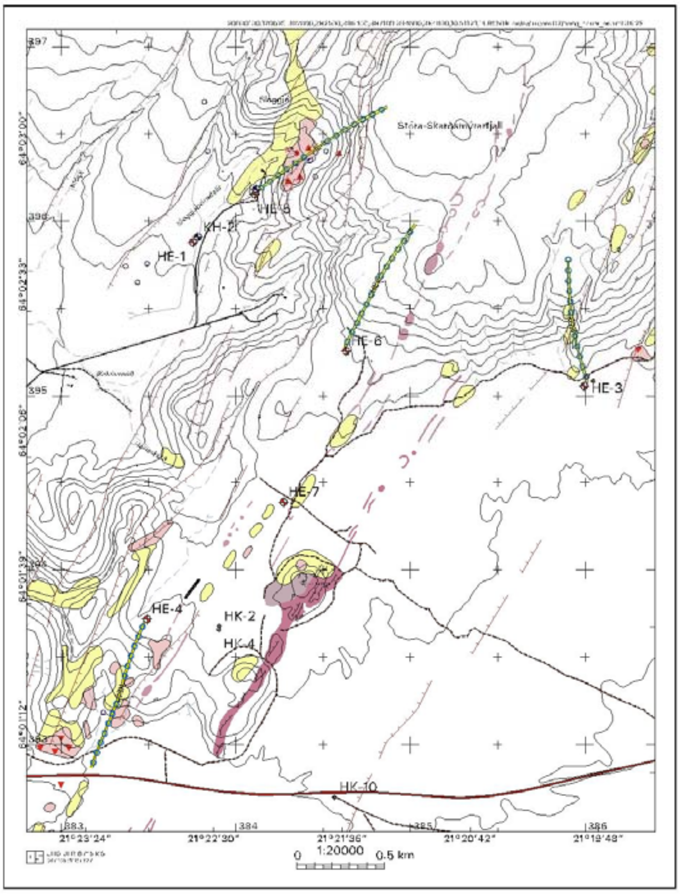
More details of the hydrothermal evolution, and the prograde and retrograde patterns everywhere within the well field, available in Orkustofnun reports, and discussed in the literature cited. This conforms neatly with the measured and inferred temperature distribution within the field, and needs to be looked at if and when it comes to siting an IDDP well at Nesjavellir. The discussion here is completed by presenting Table 2, listing the potential IDDP sites, and ranking them in a priority order. The rating of permeability in Table 2 is only qualitative and relative between the drillsite options. Environmental sensitivity is considerable at Nesjavellir and a determining factor, the safest drillsite is in Kýrdalur due to higher elevation and an additional pressure head. The winter climate varies somewhat from year to year, but is most often fair for 8-9 months at Nesjavellir, sometimes longer.

Table 2. *Priority list of potential IDDP drillsites at Nesjavellir and Hengill*

Drillsite	Priority	Temperature	Permeability	Environ./safety./climate
Kýrdalur near NJ-12	**1**	Higher	Higher	Depending but safe
Kýrdalur near NJ –17	**2**	High	High	Depending but safe
Nesjavellir valley SE	**3**	Medium	High	Depending but safe
Nesjavellir valley NE	**4**	Lower	Medium	Depending but safe
Nesjavellir NJ-11	**0**	**Highest**	**Highest**	**Not safe yet** due to high P-T
Hengill centre	**?**	High	High	Undrilled field
Hengill south	**0**	Coldest	High	CP out of reach

The south and center part of the Hengill was considered for potential IDDP drill sites as well. These were introduced in earlier chapters. The central part has never been drilled. Still, the Innstidalur valley is easily accessible, but probably environmentally sensitive. To site an IDDP well there as the first drillhole, is not very sensible, and need hardly be discussed further, while its potential would be ranked high in respect to the conceptual models of the main heat source of the Hengill hydrothermal systems, on both the south and the north side.

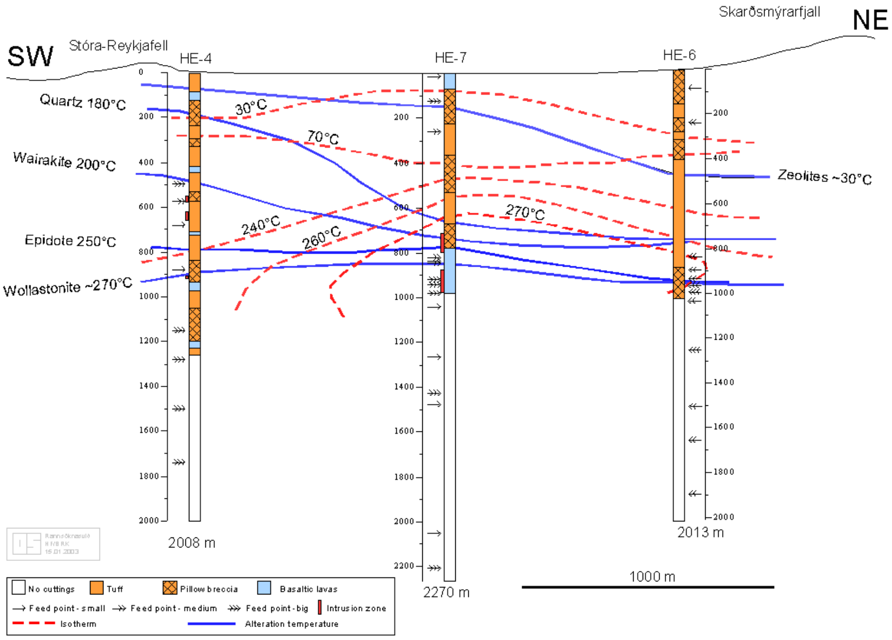
Five new wells have been sunk on the south side of Hengill at Hellisheidi, wells HE-1 to HE-5. A location map of these is shown in Figure 27 a) and a SW-NE cross-section in Figure 27 b). The highest temperature, near 270°C, is observed at intermediate depths 900-1200 m, while the bottom temperatures at about 1800-2000 m are near 220°C. The field is a liquid dominated field, apparently based on southward outflow from the Hengill center part. Permeabilities in the faulted central part of the graben zone are quite high. Total circulation losses of all drilling fluid below about 1 km depth is the case for all the 5 wells drilled in 2001 and 2002, and discussed here in the context of IDDP. Evidently, the Hellisheidi area is of little interest to IDDP based on present knowledge. Further exploration by deep drilling for other reasons might change that view in the future.



a)

Figure 27. *a) Location of new wells at Hellisheidi, south of Hengill. b) NV-SE cross section from well HE-4 to well HE-3. (legend same as in fig.21). Eruptive fissures of different ages are shown in shades of blue color, the 2000 year old fissure in the center, the 5500 year old one further to the west close to wells HE-4, HE-7 and HE-6.*

b)



3.3 Geology of the Krafla Field

In 1975 a 55-60 MW_e geothermal power plant was commissioned in Krafla. Surface exploration had been carried out during 1970-1973. Two exploration wells drilled to 1100 and 1200 m depth in 1974, and three production wells added in 1975. The volcanic eruptive episode started in December 1975, at the same time as the power plant was being constructed. A few months later, volcanic gases invaded the main production zone of the reservoir. Gas concentration in the geothermal fluid increased drastically and the pH of the fluid dropped severely. Mostly for that reason an increased effort was laid on drilling and exploitation of the Suðurhlíðar drill field where the gas invasion was not detected, east of the main upflow zone, and three wells were drilled in the Hvíthólar field by the caldera rim, several km south of the power plant. By 1984, 24 wells altogether had been drilled in three well fields. Unit-1 (30 MW_e) was in operation from 1978, initially yielding some 7 MW_e, but by 1984 excess steam was available. The installation of unit-2 was postponed.

For the next decade, the well field was monitored (see Chapter 4) for decline in volcanic gases and other parameters. Two exploration wells were drilled, in 1990 and 1991 (wells 25 and 26). Following a steady decline in volcanic gas emission a decision on drilling several production wells within the earlier abandoned drill field was taken in 1996 and 8 productions wells were sunk in the following 3 years (Table 3) to supply the 2nd 30 MW_e. turbine. As expected the best producers of high pressure steam intersected the main upflow zone in Hveragil, such as wells No.30 and No.34. The recovery of the field after the volcanic episode and successful drilling results, encouraged Landsvirkjun to make plans to enlarge the power plant by 40 MW_e (Gudmundsson, 2001). Drillhole locations within the three drill fields in Krafla are shown in Figure 29.

Table 3. *Total output of high and low pressure steam from well No.27-34.*

Well no.	**Depth** **m**	**HP steam** **kg/s**	**LP steam** **kg/s**	**Total** **MWe**
27	1,771	6.5	1.5	3.2
28	1,003	0.0	9.0	2.7
29	2,103	4.8	0.4	2.3
30	2,054	30.3	0.2	13.7
31	1,440	4.9	0.0	2.2
32	1,875	14.0	0.3	6.4
33	2,011	19.9	0.9	9.3
34	2,002	43.6	0.2	19.7
total	**14,259**	**124.0**	**12.5**	**59.5**

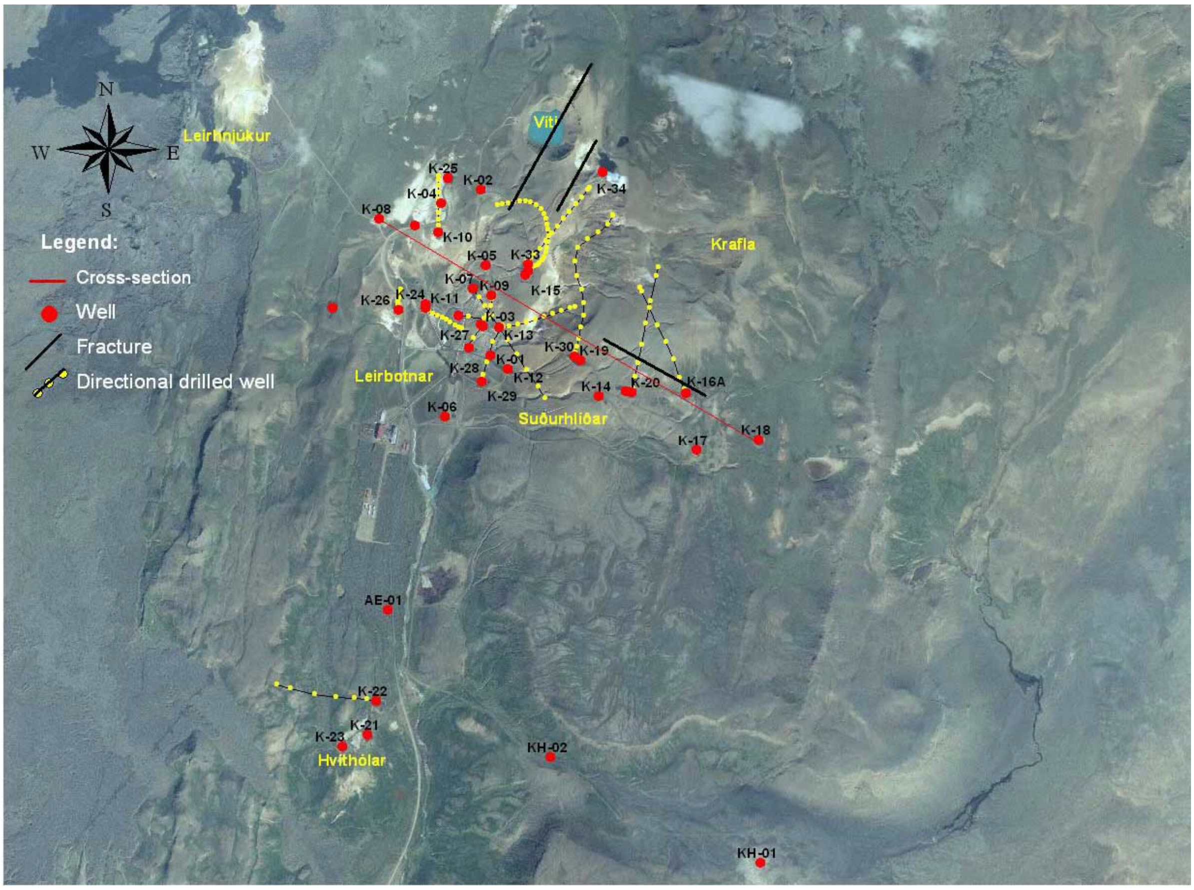
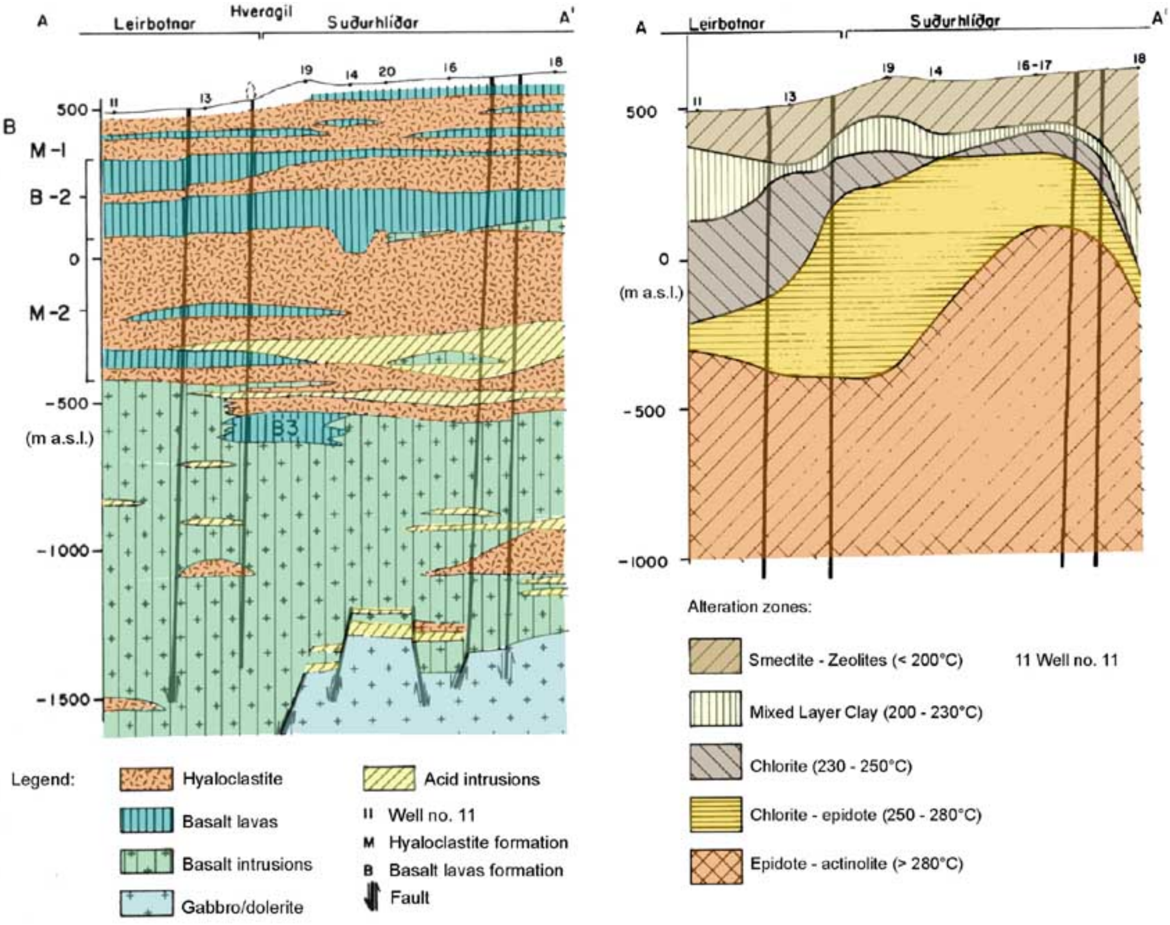


Figure 28. *Location map of drillholes at Krafla. Trajectories for inclined wells indicated. Location of cross-section from well KJ- 8 across the field to KJ-18 is shown.*

A simplified geological and alteration profile is shown in Figures 30 a,b, the location of the cross-section being shown in Figure 29. The two profiles outline the main characteristics of the Leirbotnar and Suðurhlíðar drill fields above the magma chamber, discussed in earlier chapters. The intrusive rock intensity increases drastically below about 1 km reaching up to 80-100 %. Coarse grained dolerite or gabbro intrusion(s) are shown under the eastern part of the field, cut by numerous sheeted dikes and minor intrusions (not shown). Acid intrusives (felsites-granophyre) are common at 800-1000 m depth and below. The alteration profile on the right hand side (b) clearly indicates a general rise in alteration temperature above the intrusive complex on the eastern side. The temperature range between the mineralzones is noted in brackets. Attention is drawn to well No.18, the easternmost well, being discussed within IDDP as a possible well of opportunity. A temperature decline to the east, in both mineralogy and measured temperature is pretty clear.

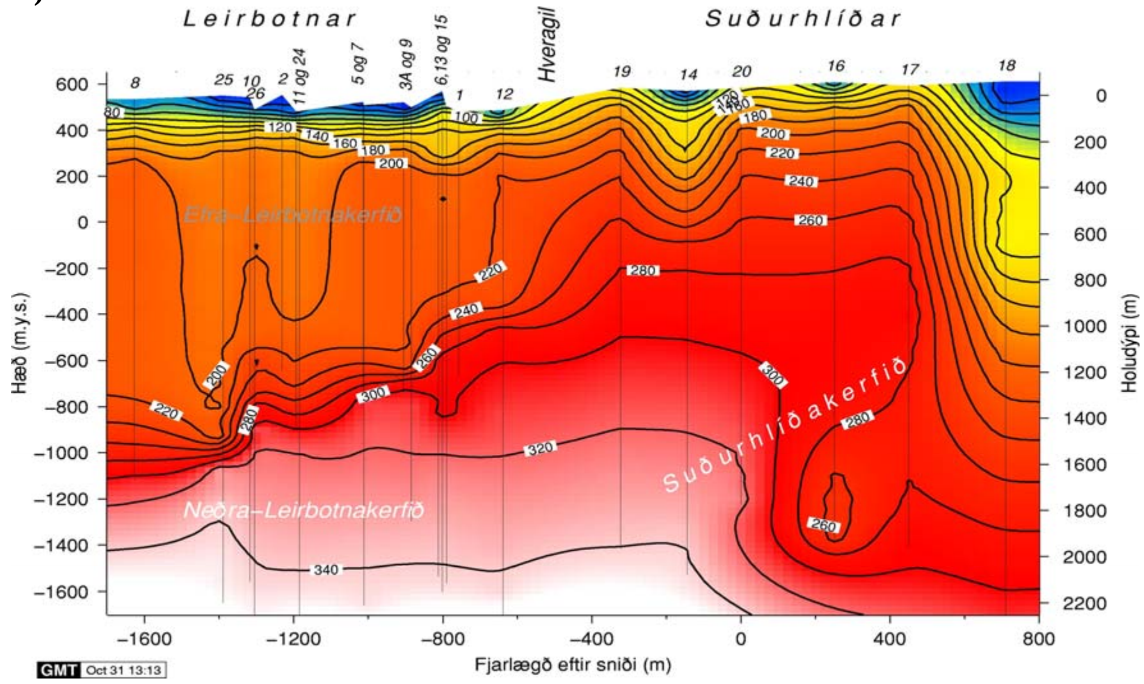
A significant decrease in intrusive rock intensity at 1-2 km depth is observed on both the south side and the north side of the magma chamber and its overlying intrusive rock complex, as seen in wells No.6 on the south side and wells No.30 and No.34 on the north side. This may be of importance when selecting a suitable drillsites for IDDP, in addition to the knowledge of the main upflow zone in Hveragil, between the two drill fields in Leirbotnar and



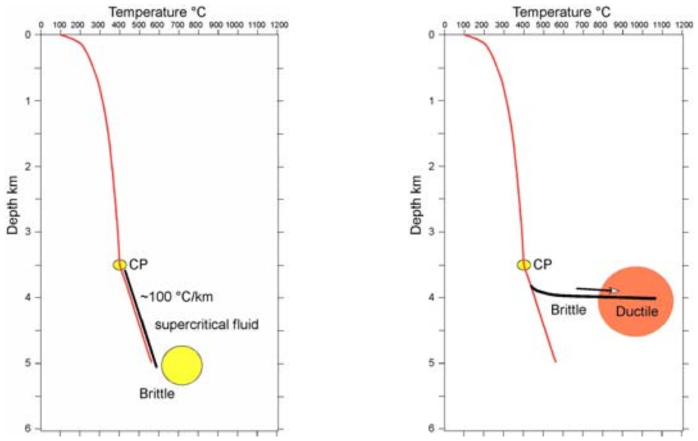
a) *b)*

Figure 29. *Geological (a) alteration (b) and temperature distribution (c) profiles across the Krafla drill field from west to east. The cross-section line is shown in Figure 28 (note the changes in scales)*

c)



Suðurhlíðar. Evidently, both high temperature and high permeability zones are favorable to IDDP. During IDDP/ICDP workshop I a presentation was given, suggesting drilling the margins of a cooling magma chamber was more favorable to IDDP than drilling straight into its top, model scenarios represented by models a) and b) in Figure 30 below, respectively. A model of this sort may apply to the Krafla drill field at depths of interest to IDDP. Looking a the temperature distribution within the Krafla drill field in Figure 29c, it is pretty evident that only about 35°C addition in temperature is needed to reach the critical point (CP) below most of the drill field on the west side. In such a situation one might expect a minimum depth of 3,5 km, or less to reach the CP. Depending on the thermal history of the cooling intrusive complex underneath the field, one concern should be a scenario like in Fig. 30b, which is not favorable to IDDP, but another concern should be the permeability. With both in view, two options for an IDDP drill site are more favorable than others, namely (**i**) the Hveragil upflow zone, which must be replenished by plentiful hydrous fluid, and (**ii**) the sides of the intrusive complex in view of the scenario in Fig. 30a. In addition to these geographical conditions need be considered. Still – quite a few sites are possible. A glimpse back to figure 29c shows a pretty neat thermal disturbances furthest to the west in the profile, both severe subsidence of the 200°C isotherm, and updoming of the 340°C isotherm. This location happens to be in line with the historic Daleldar eruption, ~1000 year old, which in turn may be responsible for some of the temperature disturbances referred to. A potential drillsite at the Daleldar fissure, pretty close to the Krafla power plant, and next to well No.26 which is used for reinjection, has been suggested during the IDDP/ICDP workshops. Similarly, the whole Hveragil upflow zone is a feasible target, at any favorable site for that matter, along it, or on the north or south side. These potential targets are indicated schematically in Figure 31.



a) *b)*

Figure 30. *Temperature scenario along the margin (a) and the top (b) of a cooling magma body at 4 about km depth, evidently at some point in time.*

A note need be added on the possible "well of opportunity", KJ-18. From the discussion above, it would evidently would be ranked considerably lower than the potential drillsites. Still KJ-18 could serve as a perfect site for a "pilot well" (as discussed in SAGA Report No.3, Appendix 1), to be used for detailed studies of the secondary mineral transition through the critical point into supercritical, possibly enabling sampling of a supercritical fluid, ideal for tool testing of coring at high temperature and prototype monitoring tools, not interfering with other activity within the Krafla drill fields. The 2000 year old Hólseldar eruptive fissure is near to KJ-18, and the magma chamber extends quite some distance east of KJ-18.

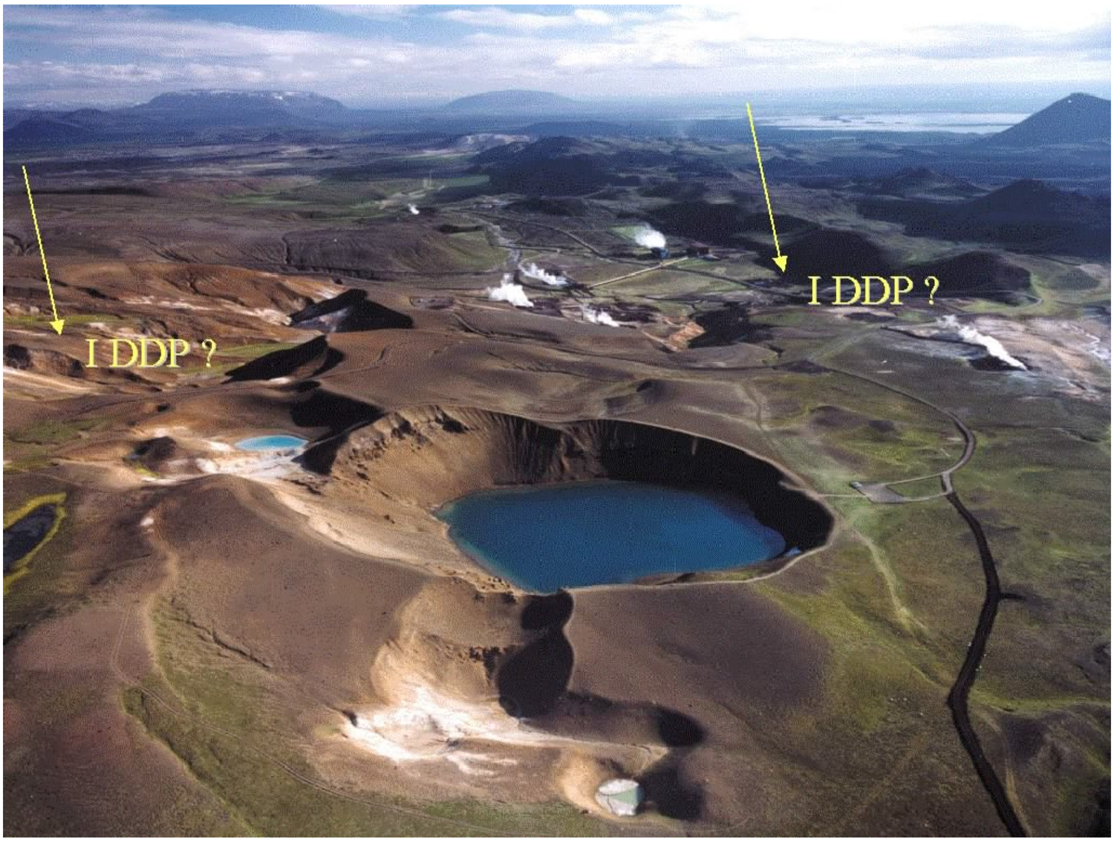


Figure 31. *A view over Víti towards the Krafla power plant. Potential IDDP drill sites in Hveragil on the left, and in Hlidardalur on the right are indicated by arrows (photo by Emil Þór).*

An attempt to prioritize the potential drill sites discussed above is shown in Table 4. The rating of permeability is both qualitative and relative to the others as in Tables 1 and 2. Environmental sensitivity and winter climate conditions vary within the drill fields.

Table 4. Priority list of potential IDDP drillsites at Krafla

Drillsite	**Priority**	**Temperature**	**Permeability**	**Environ./geography/climate**
Hveragil	**1**	High	Highest	Depending on siting
Hlidardalur	**2**	High	High	Adequate
Margin elsewhere	**3**	Lower	Medium	Depending north/south
Center elsewhere	**4**	High	Lower	Depending summer/winter
KJ-18	**5**	Lower	Low	Depending summer/winter

4 FLUID CHEMISTRY

4.1 REYKJANES

4.1.1 Model of the geothermal system

Drillhole logging shows a system with temperature and pressure in accordance with equilibrium boiling to about 900 m depth, but below that a liquid dominated system. which reaches 280 – 290°C in the NE part but is probably hotter to the SW and at greater depth. Björnsson (1998) has presented a conceptual model of the system (Figure 32). Monitoring of utilization combined with computations of mass and heat flow suggest that there is a considerable supply of heat and mass in the system and that it can be expected to be a good producer for a long time. A simple computational model for simulation has been developed (Björnsson 1999, Figure 33). The model extends from the surface to 3000 m depth and 10 km away from the center, with 10 blocks growing 100 m each, followed by 9 blocks to 10 km total radius. Horizontally the model is divided into 12 layers. The rock is divided into two types, i.e. an inner type in which temperature and pressure are changeable and a border part in which temperature and pressure do not change. There has been good agreement between observed and calculated results (Figure 34). Continued utilization is expected to reduce the pressure in the system by a few bar and cause boiling with the rise of steam to the system which in turn will cause increased surface activity. Well 10 was drilled December 1998-February 1999. It is 2054 m deep. The boiling curve is observed to a depth of 1400 m and below that the temperature is steady at 315-320°C (Franzson et al. 2001). Well 11 was drilled March-April 2002. It is 2248 m deep and a temperature of just under 300°C has been recorded. Both are relatively good producers.

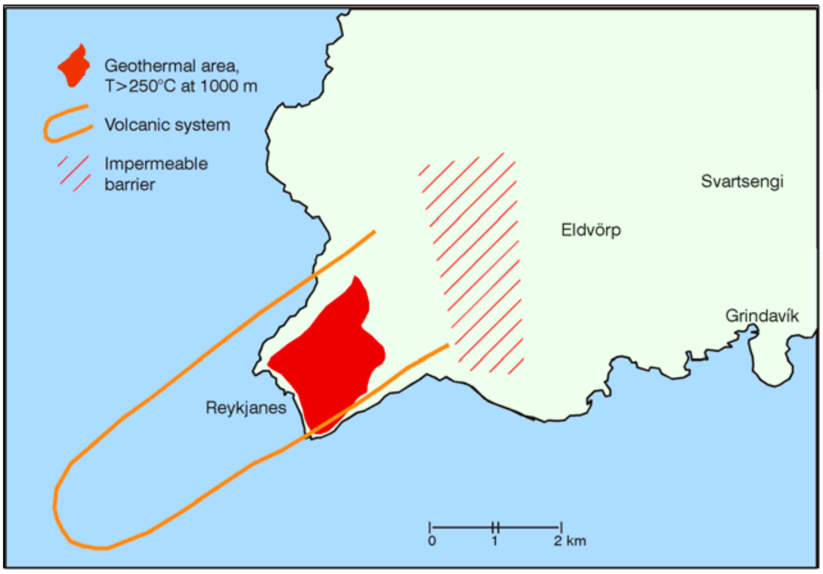


Figure 32. *A conceptual model of the Reykjanes geothermal area (Björnsson 1998)*

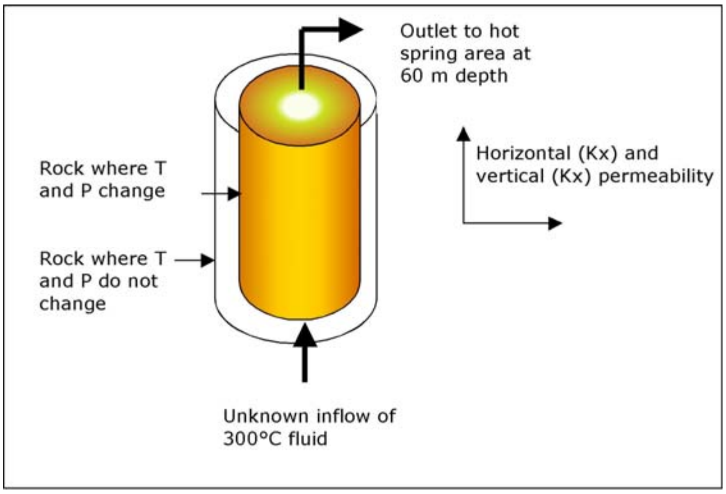


Figure 33. *Initial computational model for the Reykjanes geothermal system (Björnsson 1999).*

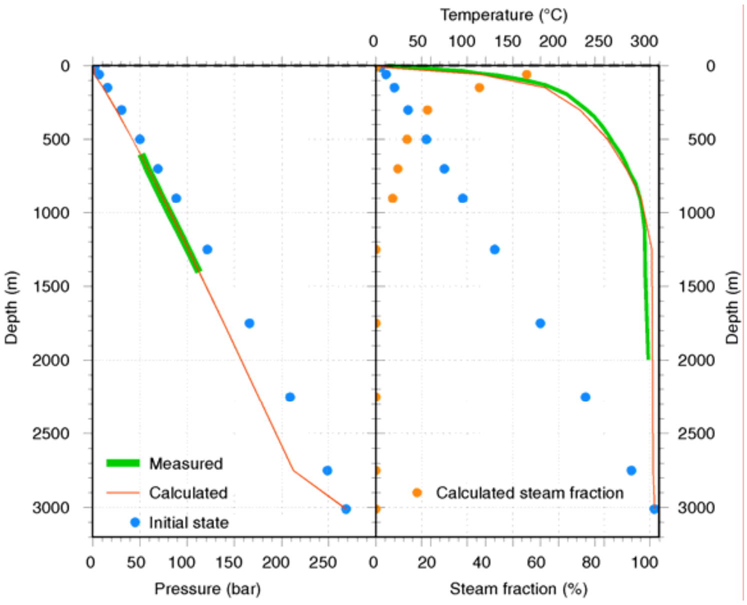


Figure 34. Simulation results for deep temperature and pressure at Reykjanes for the year 1970 (Björnsson 1999).

4.1.2 Chemical composition of the fluid

Ólafsson and Riley (1978) published chemical analyses of water from hot springs and wells 2 and 8, including results for several trace elements. They concluded that the discharge waters are formed mainly by the penetration of local meteoric water into brine-bearing formations followed by evaporation of this brine. Hauksson (1981) reviewed all chemical and isotopic data for springs and boreholes in the area that had been obtained up to that time and presented a model of the postulated flow in the system (Figure 35). His conclusion was that the borehole discharge water was derived from seawater modified by boiling, water-rock interaction and mixing with fresh seawater and meteoric water. He concluded that there was poor permeability at depth in the system and poor flow from deeper strata. Bjarnason (1984) published results for well 9 fluid as well as additional analyses for well 8 and found that the chemical composition of the fluid from the two wells was practically identical. Sveinbjörnsdóttir et al. (1986) and Kristmannsdóttir and Matsubaya (1995) have studied the isotopic (δD, $\delta^{18}O$) composition of the fluids and minerals of the system and related to alteration mineralogy. The former conclude that for a part of the history of the Reykjanes geothermal system its deeper part has been dominated by meteoric water, rather than seawater, circulation, which probably reflects melt-water input or changing sea-level during glaciations. This should be borne in mind if the Reykjanes system is to be used as a model for sea-floor hydrothermal metamorphism. The latter state that their results are compatible with an origin in a mixture of sea-water and fresh groundwater with about 80% of the present salinity of Svartsengi-Eldvörp brine followed by evaporation, or alternatively the reaction of brines with sheet-silicates formed at a stage of more dilute water, may have changed their isotope ratios. Lonker et al. (1993) concluded that at an earlier stage the system was hotter and meteoric, possibly glacial melt-water.

The chemical composition of the fluids from wells 8 and 9 is compared with the composition of sea water in Table 5. The most important deviations from sea water chemistry are magnesium and sulphate depletion and increase of silica, potassium and calcium concentrations all to be expected at high temperatures. The gas concentrations show CO_2 to be the major gas but a relatively low H_2S concentration compared to fluid from many other geothermal areas. There is a significant N_2 concentration suggesting that flow from the surface contributes to the fluid. The H_2 and CH_4 concentrations are relatively low, the H_2 concentration reflecting the temperature of the aquifers and the CH_4 concentration suggesting that little or no gas is derived from organic remains in the area. The composition of fluid from wells 10 and 11 is essentially similar.

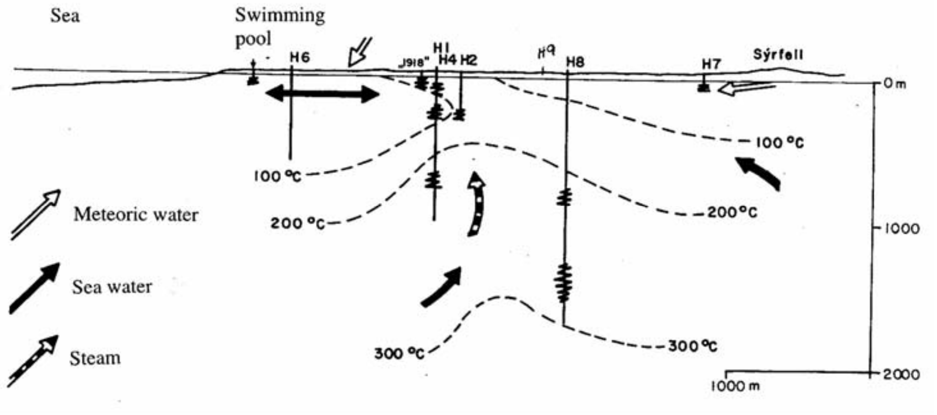


Figure 35. *Suggested temperature distribution and flow paths in the Reykjanes geothermal system (Hauksson 1981).*

From the brine in well Rn-8 in Reykjanes downhole scales of iron-magnesium-silicates have formed. Metal sulfides with high contents of precious metals have been precipitated at the wellhead in all producing wells, but are much more prominent in well Rn-9 than in well Rn-8. They are also prominent in well-11 but well-10 has only discharged for a short time so that the opportunity for observation of scales has not yet arisen. The sulfide mineral sequence observed is: Sphalerite, chalcopyrite, pyrrhotite and galena. The conditions for formation of the silicates are not well known, but the sulfides show a clear relation with temperature and pressure and regular sequential precipitation with reduced pressure. The chloride-rich fluids favor the transport of metals which form complexes with chloride, such as the base metals (Zn, Cu, Pb etc.). Boiling causes loss of CO_2 which increases pH in the liquid phase and thus tends to destabilize chloride complexes, while H_2S loss favors the precipitation of metals transported by sulfide complexes (Harðardóttir et al. 2001).

***Table 5**. Composition of total fluid (mg/kg) in drillholes RN-8 and RN-9 and of sea water at 35 ‰ salinity (Turekian 1969).*

	Well RN-8*	Well RN-9*	Sea water
°C	275	290	
SiO_2	553	647	6.4
Na	9488	9572	10800
K	1438	1419	392
Ca	1591	1632	411
Mg	1.28	0.91	1290
SO_4	21.8	14.1	2712
Cl	18732	18640	19800
F	0,17	0.14	1.3
Al		0.09	0.001
Fe		0.47	3.4
Sr		6.6	8.1
B		7.6	4.5
Mn		2.4	0.0004
Li		3.5	0.17
Pb		0.002**	
Zn	0.07***		0.005
Rb	3.7***		0.12
Cu	0.01***		0.0009
Cr		0.002	0.0002
TDS	32147	32860	35000
CO_2	1005	1536	
H_2S	27	45	
H_2	0.08	0.13	
CH_4	0,09	0.07	
N_2	2,02	3.68	

* Database Orkustofnun. * *After Kristmannsdóttir et al. (1996). * **From Ólafsson & Riley (1978)

4.1.3 Reykjanes – Conclusions

The heat source is apparently rather deep-seated and for this reason relatively deep drilling may be needed to reach supercritical conditions. The fluids encountered so far in this system are relatively saline and there is no reason why deeper fluids should not be saline too. Other factors being equal higher pressure and temperature and therefore greater depth are needed for supercritical conditions if the fluid is saline than if it is dilute. As the fluid is modified seawater and the system is known to extend into the ocean fluids from geothermal systems on the sea-floor are probably the most representative for calculations of possible properties of fluids at supercritical conditions in this system. Sea-floor systems at very high temperatures and pressures (Black smokers) are known (e.g. Campbell et al. 1988) and in fact a sea-floor geothermal system is known on the Reykjanes ridge about 50 km south-west of the system presently described (Ólafsson et al. 1991). Some modeling of the chemistry of such systems exists (e.g. Bowers 1989, Bowers and Taylor 1985).

4.2 HENGILL – NESJAVELLIR

4.2.1 Nesjavellir – Reservoir Characteristics

Within the greater Hengill volcanic system there are several geothermal reservoirs, which seem not to be interconnected. One is the Nesjavellir system and its geological features and geothermal characteristics are fairly well known down to about 2 km depth, because of numerous studies carried out under the development phase and monitoring during production. The data has been used to construct a numerical model of the field (Figure 36), and experience has shown that the model generally predicts changes in flowrate and enthalpy from the wells reasonably accurately (Steingrímsson et al., 2000).

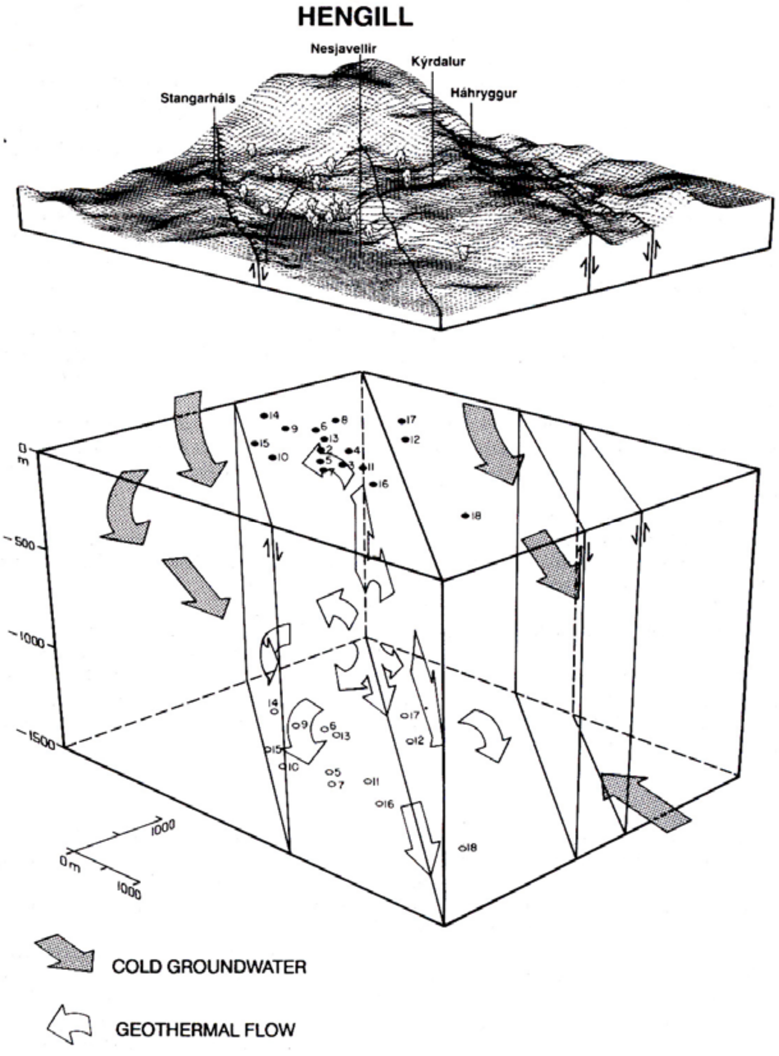


Figure 36. A three-dimensional conceptual model of the Nesjavellir reservoir.

The stratigraphy is dominated by a succession of layers of basaltic lavas, formed during interglacial periods, and irregular layers of palagonite formed by eruption under glaciers. Intrusive rocks increase in volume with increasing depth. The stratigraphy is cut by faults, generally with a NE-SW direction, which influences the permeability greatly. The faults form a graben through the field, and the most intensive geothermal activity takes place within this structure. Many of the faults are seismically active and some have acted as feeders during eruptions, such as the latest eruption about 2000 years ago on the main fault on the western escarpment of the geothermal field, the Kýrdalur fissure.

The main aquifer found in the producing wells is at 1000 to 1500 m depth and the aquifer temperature is in the range of 260-290°C, but temperature >380°C has been encountered in well NJ-11. The boreholes can be divided into three different groups according to their properties. The best producers, and those with highest enthalpy are found immediately east of the Kýrdalur fissure (see map in Figure 21, wells NJ-21, NJ-22, NG-6, NG-9, NJ-13, NJ-19, NG-11, NG-5 and NJ-16), with initial enthalpy 1700 – 2600 kJ/kg and aquifer temperature generally close to 290°C. The enthalpy of the boreholes farther to the east was lower (1200 – 1600 kJ/kg) and the aquifer temperature is close to 270°C (Figure 21, wells NJ-20, NJ-14, NJ-15, NG-10 and NJ-7). The third group of wells is west of the central graben and west of the Kýrdalur fissure. Their enthalpy is 910 – 1400 kJ/kg and aquifer temperature 220 – 260°C (Figure 21, wells NJ-17, NJ-12 and NJ-18). None of the boreholes in the last group is connected to the power station, whereas all the other wells are.

All wells east of the Kýrdalur fissure are drilled into a two-phase reservoir, as the enthalpy indicates, but the steam/water ratio differs, initially the steam ratio in group I boreholes was between 40 – 60% by weight, but the figure for group II boreholes is 5 – 20%. Production has influenced the steam/water ratio of the inflow into boreholes (Figure 37) (Gíslason, 2000).

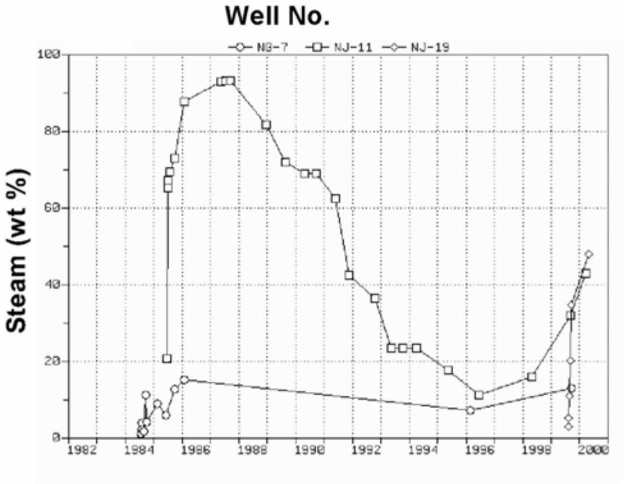


Figure 37. *Steam ratio in feeder zones in selected wells.*

4.2.2 Hengill – Chemistry

The fluid at Nesjavellir is relatively dilute, with total dissolved solids in the range of 1000–1500 mg/kg. The chemistry indicates equilibrium between water and rock in a temperature range of 270–290°C (Figure 38). The water is carbonate-rich, and initial chloride concentrations were exceptionally low, especially in group I boreholes (Figure 39), with chloride levels as low as less than 10 mg/kg. The composition of one group I well (NJ-16) deep fluid about two months after start of discharge is shown in Table 6 along with analyses from some other Hengill boreholes. With increasing utilization and the accompanying changes in enthalpy (Figure 37), this dilute water has disappeared, and chloride levels have increased gradually.

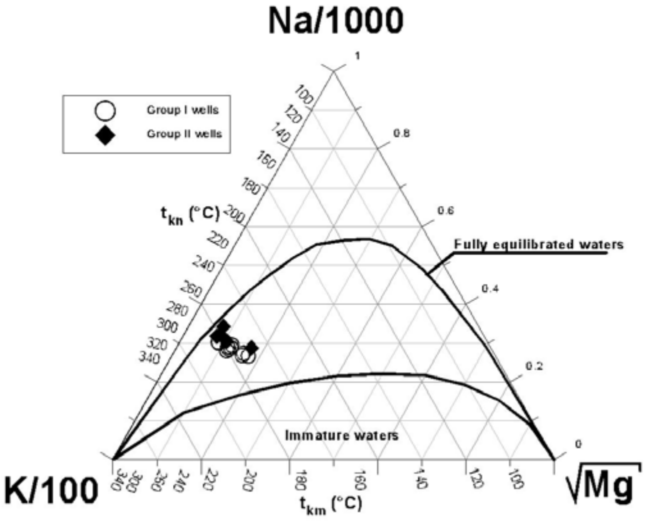


Figure 38. Nesjavellir, Na-K-Mg diagram (Giggenback 1988).

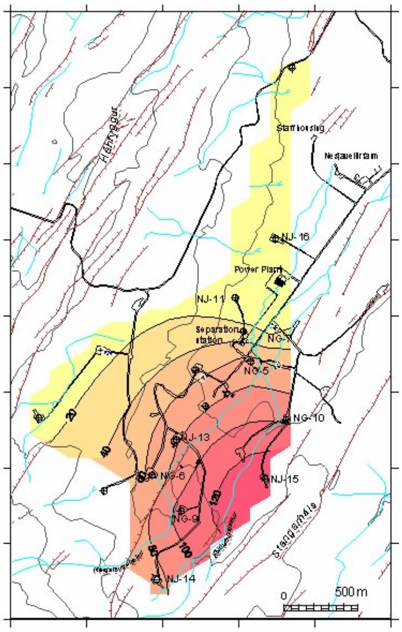


Figure 39. Cl $^-$ (ppm), Nesjavellir reservoir, the highest conc. (red) above 120 ppm Cl $^-$, and the lowest (yellow) below 20 ppm.

Table 6. *Chemical composition of deep fluid in well NJ-16, Nesjavellir 1986.04.03 (Steingrímsson et al. 1986), well G-6, Ölfusdalur, Hveragerði, well KhG-1, Hellisheiði and well ÖJ-1, Ölkelduháls*

Deep water	**NJ-16**	**G-6**	**KhG-1**	**ÖJ-1**
Date	3.4 1986	13.2 1980	17.10 1986	21.9 1995
Ref. Temp (°C)	290	210	270	198
SiO_2	718.5	337	538	337
Na	83.8	158	127	172
K	16.9	16.3	18.5	17.1
Ca	0.53	2.06	0.30	1.37
Mg	0.021	0	0.002	0.0062
SO_4	12.3	30.2	16.7	33.6
Cl	10.2	166	7.4	170
F	0.78	0.93	1.11	0.79
CO_2	57.4	37.4	220	333
H_2S	0.72	22.7	56.0	32.9
H_2	0.72	0	0.011	0.006
O_2	0.01	0	0.003	-
CH_4	0.02	0	0.035	-
N_2	0.47	0.04	0.679	0.243
Deep steam				
CO_2	2510	2317	8136	-
H_2S	1538	301	432	-
H_2	160	4.9	4.4	-
O_2	1.1	2.0	1.2	-
CH_4	7.2	2.5	16.7	-
N_2	125	102	409	-

The oldest geothermal system within the Hengill volcanic complex is the Hveragerði field. As is to be expected the chemistry of the fluid there shows equilibrium with a lower temperature, and the chloride level is higher than is found at Nesjavellir, although the water is dilute (Table 6).

Currently the Hellisheiði geothermal system is under investigation, and a total of 6 deep boreholes have been drilled, one in 1985 and five in 2001 and 2002. Four of the new wells are currently being flow tested but the fifth is still warming up. Chemical data (still incomplete) is available for two wells, and it indicates equilibrium at 255–275°C.

Information on water chemistry in other geothermal systems of the Hengill volcanic complex is less known. One well has been drilled and tested at the Ölkelduháls field (well ÖJ-1), but other geothermal systems within the Hengill volcanic complex have not been tested by drilling. In Table 6 the chemical composition of fluid from selected wells in the Hengill area are shown

4.2.3 Hengill – Conclusion

Investigation of the Hengill volcanic complex indicates that super-critical conditions at shallower depth than 5 km are likeliest to be found associated with the youngest volcanic structure in the western part of the complex. Of the geothermal systems, the Nesjavellir area is best understood, the Hellisheiði field is under investigation, but the Innstidalur field, located between Nesjavellir and Hellisheiði fields, is least investigated

At 1-2 km depth at Nesjavellir the geothermal reservoir is two-phase with temperature and pressure increasing with depth along the boiling point curve. The aquifer system near the bottom of well NJ-11 could not be quenched with cold water circulation, suggesting initial aquifer pressure above 220 bar and the temperature was at least 380°C. If the fluid at the bottom is dilute fluid of the type observed elsewhere in the Nesjavellir system these conditions would lead to a supercritical fluid state in the aquifer (Steingrímsson et al. 1990). The system is a satellite system and therefore likely to have reached some sort of equilibrium after magmatic gases were emitted from the magma reservoir and therefore the fluids are not likely to be vicious. Thus it is likely that at Nesjavellir supercritical conditions can be reached at a relatively shallow level with relatively little danger of serious utilization problems.

The investigation of the Hellisheiði geothermal system by deep drilling is still at an advanced stage. Preliminary interpretation indicates a strong flow control by faults, and all except the oldest well reach a temperature maximum at 900 – 1400 m, and encounter lower temperatures at deeper levels. The main upflow zone appears to be outside the Hellisheidi field, presumably closer to the Hengill center as suggested in the model in figure 10.

4.3 KRAFLA

4.3.1 Chemical composition of the well fluids

Ármannsson et al. (1987) divided the fluids from Krafla wells into seven groups according to chemical composition and geography: Leirbotnar upper zone (1), Leirbotnar lower zone N (2) and S (3), Hveragil (4), Suðurhlíðar (5), Hvíthólar upper (6) and lower parts (7). Isotopic ratios suggest two sources, local (for Leirbotnar) and nearby mountains (for Suðurhlíðar and Hvíthólar) (Darling and Ármannsson 1989). All these groups contain dilute waters close to neutral pH. Bicarbonate is usually the major anion in deep water when a boiling fraction is present and when excess magmatic gas is present. In Leirbotnar, upper zone, Leirbotnar S lower zone, Hveragil and in the upper part at Hvíthólar there is more sulphate than chloride. In Leirbotnar N lower zone, Suðurhlíðar and the lower part of Hvíthólar there is more chloride than sulphate in the liquid phase. Magmatic gas has probably affected the composition everywhere but it is more likely that excess is only observed in the areas closest to the magmatic inflow and equilibrium is not established. Recent literature on gas emanations from volcanic areas suggests that more gas rises to the surface in a steady stream of volcanic gas through soil (e.g. Chiodini et al. 1994, Klusmann et al. 2000) than through fumaroles and wells. Attempts to simulate geothermal fluid composition in the Krafla system by titrating Krafla rock with local groundwater suggest that the geothermal fluid composition cannot be derived from water and rock alone, volcanic gas must have been added too (Ármannsson 2001). In Table 7 deep water and deep steam composition calculated using the program WATCH (Arnórsson et al 1982) for selected samples from each of the seven groups is presented.

4.3.2 Effects of magmatic gases

Based on surface activity and properties of well fluids at least four sub-fields, Leirhnjúkur, Leirbotnar, Suðurhlíðar and Hvíthólar (Figure 28), have been identified.

Leirhnjúkur and Leirbotnar were affected by magmatic gas during the volcanic activity 1975-1984. Leirhnjúkur has never been drilled but the other three have. In fact drilling was moved from Leirbotnar to Suðurhlíðar and later Hvíthólar because no signs of magmatic gas were found in fumarole fluids from the latter two.

Magmatic gas was identified by a large gas concentration in the steam, mostly carbon dioxide and hence by the ratio of carbon dioxide to other gases such as hydrogen sulphide (Ármannsson et al. 1982). The carbon dioxide concentration of the fluid in well KG-3 and, when that well collapsed, in the nearby KJ-7, was monitored and found to reach maximum 1977-1979 and then decrease (Figure 40). The gas seemed to wane sooner in Southern Leirbotnar and Leirhnjúkur than in Northern Leirbotnar near Víti (Ármannsson et al. 1989).

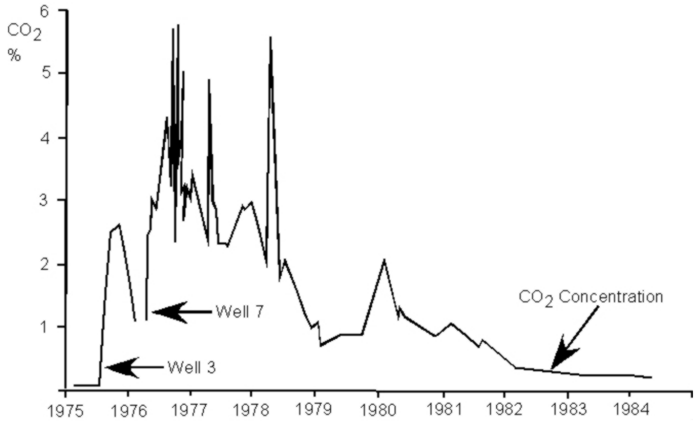


Figure 40. *CO_2 concentration in well KG-3 and then well KJ-7 fluid 1975-1984.*

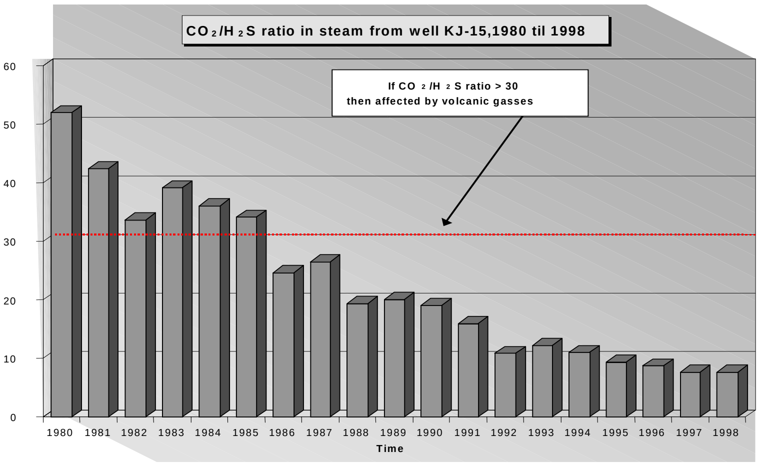


Figure 41. *Well KJ-15 CO_2/H_2S 1980-1998 (Guðmundsson 2001).*

Gas changes in well KJ-15 illustrate this. Figure 41 shows changes in the CO_2/H_2S ratio in well KJ-15 1980-1998. Concomitantly the flow from the well has increased. The gas concentrations and ratios along with different temperature profiles for the individual sub-fields (see figure 14) were instrumental in constructing a conceptual model of the Leirbotnar and Suðurhlíðar sub-fields (Figure 42) and this has been used with small changes as a basis for modeling to date. The most obvious consequences of the magmatic gas incursion was the formation of massive deposits in the wells. These consisted of iron sulphides (pyrite, pyrrhotite) and iron silicates with traces of other deposits (Ármannsson et al. 1982). The gas incursion was first observed in early 1976. At the same time well KG-4 which had been drilled in Northern Leirbotnar in 1975 went out of control and turned into a boiling pond and by March the pH of water in a stream flowing from it was 1.86, which suggested a different fluid from the one flowing from the well during its early discharge. Reduction in the flow from the well and a change in the composition suggesting flow from the upper zone of the Leirbotnar field suggests that the lower part of the well (and the gas flow with it) was blocked, probably by deposits. Well KG-10 was drilled in Northern Leirbotnar in 1976 and very soon became blocked by deposits and also showed signs of very acid fluids in the lower zone before it was blocked. Well KG-25 was drilled close to well KG-4 in 1990 and also contained acid fluids. Its flow declined but it seemed to be due to damage to the liner by corrosion rather than deposits (Ármannsson and Gíslason 1992). The acid fluids are apparently still present although the magmatic gas has disappeared.

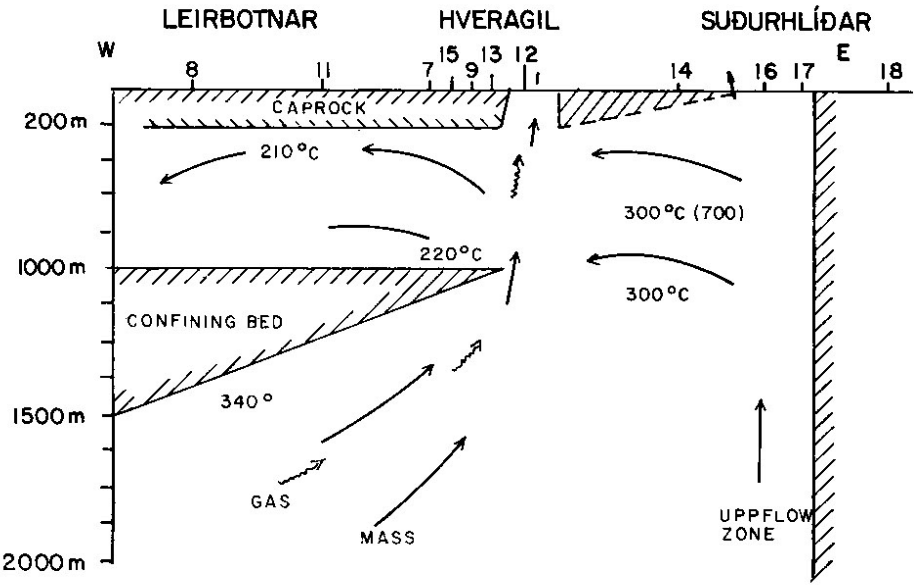


Figure 42. *A conceptual model of the Leirbotnar and Suðurhlíðar subfields (Stefánsson 1981)*

4.3.3 Superheated steam and brine

Well KG-12 started discharging at the end of November 1978. The steam fraction of the flow increased until early January 1979 when it was discharging dry steam. Temperature and pressure measurements suggested that this steam was superheated, i.e. the measured wellhead temperature was considerably higher than the equilibrium temperature corresponding to the measured wellhead pressure. Analysis showed that this steam contained about 100 ppm chloride and caused corrosion to the wellhead upon condensation followed by erosion of the turbine blade.

Hydrothermal alteration minerals are likely to buffer the fluid but the invasion of magmatic gases may have disturbed mineral-water equilibria and caused a decrease in pH (as possibly happened in Leirbotnar N). Vapour containing about 100 ppm HCl as was observed can be boiled at 350°C from a liquid containing 10.000 to 80.000 ppm at the probable pH of 5 to 6. If the pH range is narrowed to 5.5-5.7 as was observed in a brine that emerged once in a pulse from the nearby well KJ-7 the chloride range in the liquid corresponding to the above chloride concentration in vapour is 30.000 to 40.000 ppm. During its early days well KG-12 fluid was superheated and the flow sporadic and there is an apparent relationship between the extent of superheating and the chloride concentration (Truesdell et al. 1989). In 1981 superheating and chloride concentration decreased and both became insignificant in 1982. Results of isotopic determinations suggested that at the same time discharge from the well changed from being primarily Hveragil fluid to being Suðurhlíðar fluid (Fig.25, Darling and Ármannsson 1989). No signs of brine have been observed in Suðurhlíðar.

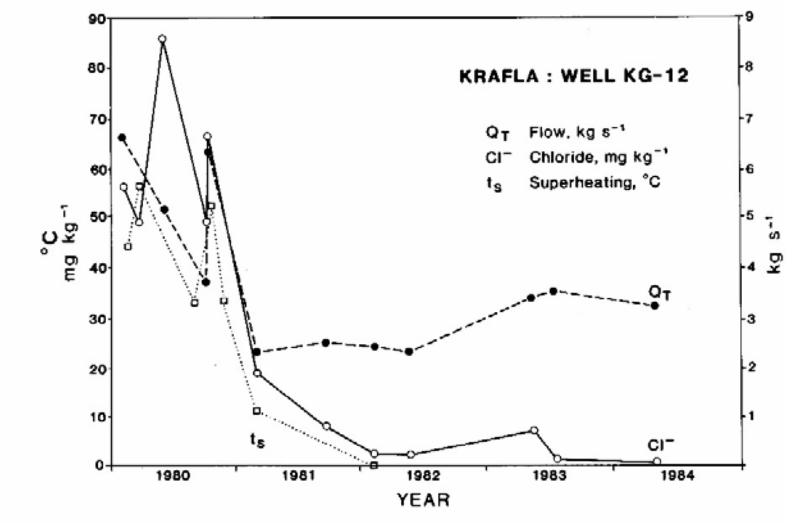


Figure 43. *KG-12. Flow, extent of superheating and Cl- concentration 1980-1984.*

Table 7. *Deep water and deep steam composition of selected Krafla well fluids.*

Group No.	1	2	3	4	5	6 1)	7	Námafjall
Well No.	KG-8	KG-26	KJ-13	KJ-20	KJ-14	KJ-22	KJ-21	BJ-12
Date	84.09.29	9207048	3.10.29	82.11.25	81.08.21	83.09.12	85.05.09	92.04.30
Ref. Temp°C	210	310	310	285	295	210	270	259
Boiling p. %	0.14	0	0.24	0.21	0	0.11	0.18	0.53
Deep water								
PH	7.96	7.13	7.83	7.31	7.77	7.70	7.59	7.49
SiO_2 ppm	351.5	793.6	645.6	665.5	726.0	325.6	505.5	522.7
Na ppm	179.5	357.6	165.4	153.2	165.8	116.8	138.0	120.6
K ppm	21.08	81.46	26.42	36.05	34.02	11.43	25.02	20.75
Ca ppm	1.58	28.93	3.16	0.80	0.55	2.32	0.61	0.30
Mg ppm	0.00	0.077	0.005	0.004	0.008	0.009	0.000	0.010
SO_4 ppm	170.5	61.97	134.7	43.73	14.38	83.18	23.68	9.88
Cl ppm	1.60	610.7	27.37	91.76	78.79	49.67	115.8	79.05
F ppm	1.02	3.78	0.89	0.69	4.71	0.96	0.78	0.50
TDS ppm	905.8	2030	1564	1107	1263	663.4	943.5	1023.7
CO_2 ppm	94.64	367	396	676	497	52.96	114.6	31.11
H_2S ppm	53.0	99.46	111.0	102.6	42.44	30.71	78.76	142.8
H_2 ppm	0.00	0.20	0.36	0.16	0.00	0.00	0.10	0.47
O_2 ppm	0.02	0.05	0.01	0.05	0.00	0.00	0.00	0.04
CH_4 ppm	0.03	0.01	0.00	0.01	0.00	0.00	0.01	0.03
N_2 ppm	0.43	0.83	0.14	0.54	0.00	0.00	0.12	0.22
Deep steam								
CO_2 ppm	4948	13486	11927	39818	19392	4630	7152	2314
H_2S ppm	581	1091	873	1627	411	587	1172	2481
H_2 ppm 6.9	25.3	44.7	39.9	0.00	0.00	37.9	256	
O_2 ppm 41.3	6.0	0.92	11.86	0.00	0.00	1.61	17.10	
CH_4 ppm	112	2.5	0.00	6.0	0.00	0.00	7.5	21.4
N_2 ppm	1206	128	22.4	167	0.00	0.00	55.4	142

1) Mixture of 6 and 7

4.3.4 Námafjall

The heat source for the nearby Námafjall geothermal system is connected to that of Krafla by way of a dyke (Figure 44), as was witnessed by the lava eruption through well B-04 (Larsen et al. 1979). Presumably, a complex of cooling intrusions, originally emanating from the Krafla magma chamber, are trapped at depth below the Námafjall drill field. The fluid however has a different origin, probably far to the south according to interpretation of isotope ratios (Darling and Ármannsson 1989). The system is relatively uniform in chemical composition. Calculated deep water and deep steam composition for one of the deep wells, BJ-12 is shown in the last column of Table 7.

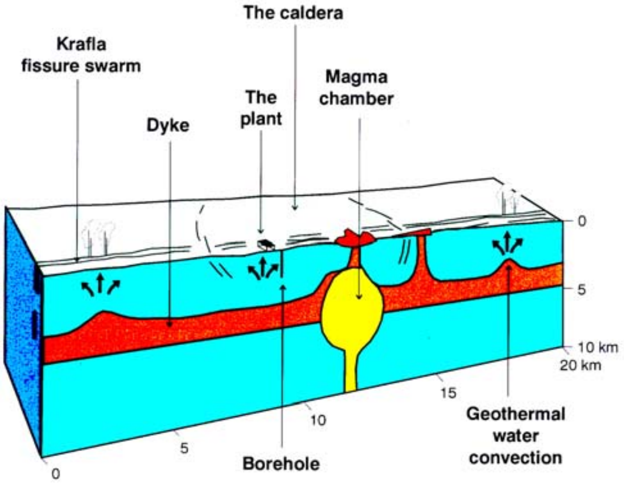


Figure 44. *The Krafla magma chamber and dikes that conduct magma and heat to nearby geothermal systems (After Björnsson et al. 1979).*

4.3.5 Krafla - Conclusions

The heat source is relatively shallow and high temperatures should be reached relatively easily by drilling. The closeness to the magma chamber may bring problems such as those encountered during the 1975-1984 episode, manifested in extensive deposits and acid fluids. The reservoir fluid is apparently dilute and easy to handle but there are signs that there may exist a more saline brine at greater depth from which HCl-rich steam can boil. The experience in Námafjall suggests that it is possible that the magmatic fluids may have reacted to a greater extent, the system approached equilibrium more closely and that the reservoir fluid is more benign if the heat source is secondary, e.g. a dyke complex.

5 PREDICTION ON DEEP FLUID CHEMISTRY

5.1 Introduction

Dr. Valgardur Stefánsson of the SAGA group commented after the first meeting that a chemical study whose results would indicate whether rapid plugging or corrosion would be likely or not at the target depth was a prerequisite for drilling. As a result it was decided to carry out a study using presently available data on fluid chemistry at such conditions and the reaction path program CHILLER with the database SOLTHERM (Reed and Spycher 1998) which can be employed in the temperature range 25-590°C to compute the likely composition of the target fluid and how it is likely to behave.

5.2 Conditions

The study involves rock, water and gas. The rocks are seen to differ especially with depth. At great depth intrusions often acidic are relatively common in Krafla. Therefore it is likely that the fluid at the target depth might be interacting with acidic rock. In Nesjavellir intrusive rocks are basaltic to intermediate but in Reykjanes only basaltic rocks have been observed. One of the aims is to carry out calculations with basaltic and acidic rocks and find out whether this makes a difference. Earlier experience suggests that fluids interacting with acidic rocks are high in fluoride.

5.3 Earlier work

Previous calculations in which Krafla ground water was reacted with altered Krafla basalt and volcanic gas at 200-300°C showed that the addition of volcanic gas is essential to produce the type of fluid composition that is common in high-temperature geothermal areas such as Námafjall and Krafla. The same calculations also showed that the gas affected the mineralogy and also the capacity of the fluid to take up gas showing an increased capacity with increasing temperature. Therefore enormous quantities of gas are needed to saturate the fluid and cause excess gas to be present in the system. This is however what happened in parts of the Krafla system during the Krafla fires 1975-1984 and this excess gas caused the formation of deposits that led to rapid plugging of production wells. At some distance from the major upflow, such as in the southern part of Krafla and where the heat source is secondary, e.g. an intrusion such as in Námafjall, this did not happen in spite of volcanic activity. Thus it seems prudent to stay away from primary magma sources if possible.

5.4 Results of calculations

The program Chiller was applied to react basalt with seawater, freshwater and magmatic gas in the following sets of calculations.

a) Seawater-basalt reaction from 0 to 1000 grams basalt per kg of initial water, at P=1000 bar and T= 200, 300, 400 and 500°C.
b) Freshwater-basalt reaction from 0 to 1000 grams basalt per kg of water at P=1000 bar and T=400°C.
c) Cooling of seawater-basalt fluids from the 500°C reaction (a), from 500 to 150°C, taking fluids from 10g, 100g and 1000g reaction points. This calculation series is intended to simulate potential conductively cooled fluids.

d) Reaction of magmatic gas (CO_2 (0.5), SO_2 (0.25), H_2S (0.25) as mole fractions) with an already-reacted basalt-freshwater mixture (at 9 g basalt per kg freshwater).

The results show that there are no significant qualitative differences between the 400-500°C reactions and their 200-300°C equivalents The seawater reactions produced moderately acidic (pH 2.8 when cooled to 150°C) to very acidic (pH 1.7 when cooled to 150 °C) fluids owing to H^+ production by precipitation of Mg-silicates, driven by the large concentration of Mg^{2+} in seawater. Seawater sulfate is reduced to sulfide as ferrous iron reactant minerals are altered to ferric minerals, such as hematite, magnetite and epidote.

In contrast to seawater, the freshwater reaction produces high-pH fluids (e.g. 8.0 when cooled to 150°C). These fluids are also quite reduced.

Cooling of the seawater-basalt fluid yields acidic waters and “scale” or vein minerals dominated by quartz (or amorphous silica), with lesser sulfides of Fe, Cu and Zn. The details of sulfide mineral abundance and mineral ratios differs depending on the pH and redox state, which, themselves, depend on the effective water-rock ratio of the deep reaction between basalt and seawater.

Magmatic gas reaction with the freshwater-basalt mixture at 400°C acidifies and sulfidizes the system. The original rock-forming (alteration or metamorphic) minerals are partially replaced by quartz, magnetite, pyrite, and anhydrite.

The result of a preliminary simulation in which actual Nesjavellir fluid equilibrated with gas and rock at 300°C was titrated with Ölkelduháls basalt at 450°C and 400 bar suggests a benign fluid but increasing deposition with decreasing water/rock ratio.

5.5 Conclusions

In all cases there is apparently not a great danger of deposition if the fluid is maintained at a temperature close to its subsurface temperature

At Krafla there is some danger of deposition as excess gas might be present. At Reykjanes the fluid is likely to be saline and thus relatively acid and corrosive. There is also some evidence that relatively acid brine might be present deep within the Krafla system. The Nesjavellir fluid seems least likely to produce acid fluids and deposition.

6 GEOPHYSICS 1 – RESISTIVITY

6.1 Introduction

Electrical and electro-magnetic methods have been used extensively to identify and delineate high-temperature geothermal reservoirs in Iceland. All high-temperature systems, within the basaltic crust in Iceland, have a similar resistivity structure, characterised by a low resistivity cap at the outer margins of the reservoir, under-lain by a more resistive core towards the inner part. This is found in fresh-water systems as well as brine systems, with the same character but lower resistivities in the brine systems.

Comparison of this resistivity structure with data from wells shows a good correlation with alteration mineralogy. The low resistivity in the low-resistivity cap is dominated by conductive minerals in the smectite-zeolite zone in the temperature range 100-200ºC. At temperatures 200-250ºC zeolites disappear and the smectite is gradually replaced by the resistive chlorite. At temperatures exceeding 250ºC chlorite and epidote are the dominant minerals and the resistivity is probably dominated by the pore fluid conduction in the high-resistivity core. The important consequence of this is that the observed resistivity structure can be interpreted in terms of temperature distribution.

The resistivity of rocks in the uppermost 1 km of all the three geothermal areas under consideration have been mapped in some detail. They where originally mapped coarsely by DC-methods (Schlumberger soundings) in the seventies and early eighties and later re-mapped more densely by the more resolving central-loop TEM sounding method.

The sounding curves are interpreted by one-dimensional inversion, and layered models are used to compile resistivity cross-sections and maps at various depths. Based on comparison of resistivity and data from wells, an attempt is made to interpret the resistivity structure in terms of likely geothermal activity and temperature distribution.

The heat sources of the geothermal systems are normally deep seated (at some or several km depth) and the production zones of wells in conventional high-temperature utilization are generally in the depth range of 1-2 km. Experience has, however, shown that a detailed knowledge of the resistivity structure in the uppermost 1 km is a good indicator of deeper structures. Because of the convection mechanism in geothermal systems, near surface resistivity anomalies are generally found above the main heat sources at depth.

6.2 The Hengill Area

A total of 186 TEM-soundings has been carried out in the area, from 1986 up to the year 2000. There exit, in addition to the resistivity data, several other valuable data sets from the Hengill area.

The Hengill area was very active seismically in the period 1994-999. Processing of extensive micro-earthquake data has revealed active tectonic movements which are somewhat different from the fissure-swarm/graben tectonics that are most prominent on the surface. A good data set on geothermal gas concentrations in fumaroles exists, as well as gravity data and tomographic data on sound velocities in the upper crust in the Hengill area. In the following discussion an attempt is made to interpret with the different data sets, with the main emphasis on the resistivity data.

Figures 45-47 show resistivity maps of the Hengill area at different elevations (100, -100 and –600 m a.s.l.), faults and fractures from geological maps and inferred faults from seismicity (green lines), as well as fumarolic surface activity. Figure 47 also shows Bouger gravity isolines.

The main conclusion from the resistivity data is that at depths greater than 1 km, there is a large geothermal system, more or less continuous from the Grændalur-Hveragerdi volcanic centre in the east to the northwest under Tjarnahnúkur, Bitra, Mt Hengill and Skarðsmýrarfjall; it extends some 5 km under Mosfellsheiði, NW of the Hengill volcanic complex. The heat sources could be cooling intrusions associated with EW-trending tectonic faults. These faults are probably closely related to the South-Iceland transform zone (SIZS). Intrusions seem to be most intensive where EW-trending faults meet NS-trending faults, which in turn seem to connect to different zones of EW-trending faults.

Between the Hengill and the Hveragerdi volcanic centers, intrusion and geothermal activity is likely to have persisted for hundreds of thousands of years and existed during glaciation, at much higher ground-water level than at present. The rocks are highly altered, with high-temperature alteration minerals at shallow depths. The well ÖJ-1, drilled on Bitra, confirmed that a relatively cool (about 200°C) convective system is presently found in the uppermost 1 km, at least in some places. Gas geothermometers do, on the other hand, indicate higher temperatures at greater depth, but discrepancies between different gas thermometers can be interpreted as indicating cooling near surface rocks. It is therefore argued, by analogy with the geothermal system in Krafla, NE-Iceland, that near-horizontal intrusions, below 1 km depth, act as a cap-rock for a deep geothermal system with higher temperatures. A shallow convective system is found above the intrusions, mainly driven by heat conduction through the cap-rocks. The presence of dense intrusions in the area is consistent with relatively high gravity and sound velocity. The TEM-soundings show anomalies of relatively low resistivity in the high-resistivity core. They correlate with faults inferred from seismicity and are interpreted as reflecting cooled rocks. If this is the case, then a shallow cooled convective system is not just confined to the vicinity of the well ÖJ-1. It is, however, difficult to predict with any certainty how widespread this cooled upper system is, because the resistivity structure is rather complex in this area and fumaroles unevenly distributed.

To the SW of Bitra, the TEM-soundings do not indicate high temperature alteration minerals at depth in an area extending northward and into the resistivity anomaly of the geothermal system. This coincides with a NS-trending fault. The fault might therefore act as a recharge-channel for cold ground-water to flow towards the geothermal system.

The TEM-soundings indicate an intense geothermal activity under the eastern part of Mt Hengill and westward NE of the valley Innstidalur. The resistivity data do not indicate high temperatures in the uppermost 1 km in the western part of the fissure swarm under the NW part of Mt Hengill and northward. The same applies to the valley Innstidalur; the fact that resistivity increases only slightly at depth to the north of the valley might indicate limited geothermal activity in that area. A clear resistivity anomaly under Skarðsmýrarfjall indicates highly altered rocks and intensive and persistent geothermal activity.

Inside the fissure swarm, the geothermal activity seems to be most intense on the southern and northern margins of a zone where EW-trending faults intercept the fissure swarm. Extrusive volcanic production is highest in these places (Mt Hengill and Mt Skarðsmýrarfjall) and a high density of intrusions is expected at depth. The resistivity indicates generally less-altered rocks in the uppermost 1 km inside the fissure swarm than outside it, especially to the east. This is probably, at least partly, because the rocks in the swarm are younger and have not accumulated as much alteration. Gas geothermometers indicate higher temperatures at depth inside the fissure swarm than to the east and do not indicate cooling at shallow depths.

The resistivity data indicate high-temperature geothermal activity west of Mt Hengill and Húsmúli, extending some kilometres to the NW under Mosfellsheiði. The geothermal system in this area is at a greater depth, and the rocks are less altered, than on the east side of the fissure swarm. The heat sources of the geothermal activity under Mosfellsheiði are probably intrusions in the crust. Some of the intrusions have drifted out of the Hengill volcanic complex, but more recent intrusions, connected to EW-trending transforms are also thought to be present. No geothermal surface manifestations are found in this area, and tectonic activity visible on the surface occurs far less than on the east side of the fissure swarm. This can be taken as an argument against geothermal activity. The question of whether high-temperature geothermal fluids are present at depth under Húsmúli and Hellisheiði can only be answered by drilling.

The geothermal activity at Hveradalir is obviously related to the western margin of the fissure swarm. It is not clear whether it is merely an outflow from the geothermal system to the north, or if it has its own heat sources. The presence of Mt Reykjafell with relatively high extrusive volcanic production might suggest intrusions and therefore heat sources at depth. The geothermal activity in Hverahlíð does not seem to be connected to the geothermal systems in the north. It is probably driven by heat sources and higher permeability related to EW- and NS-trending faults that intercept in the area, and it is considered likely that the geothermal activity extends westward at depth, into the fissure swarm NE of Stóri-Meitill.

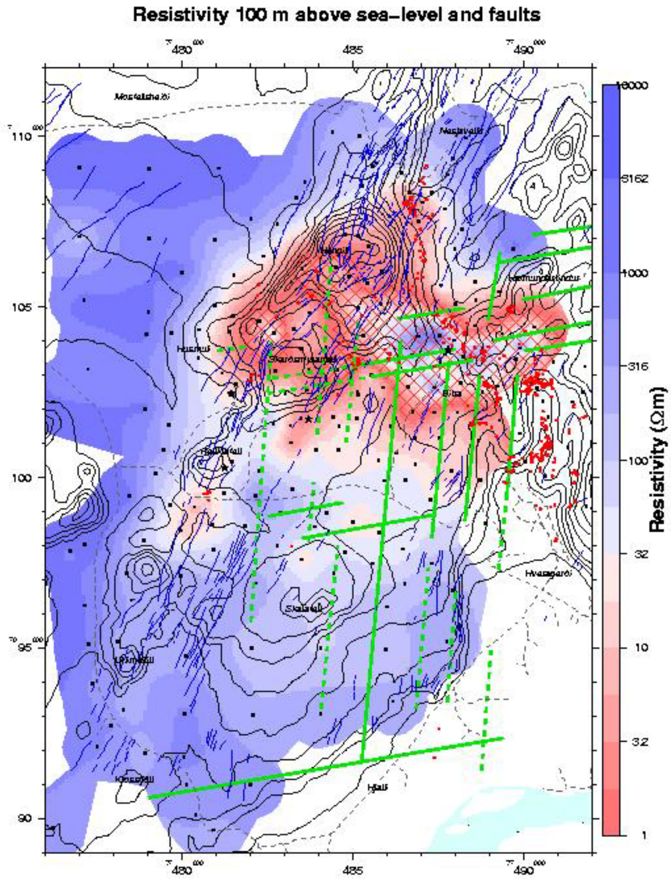


Figure 45. Hengill area. Resistivity 100 m above sea level, faults and fissures (blue and green lines), surface manifestations (red dots) and wells south of Hengill (black stars).

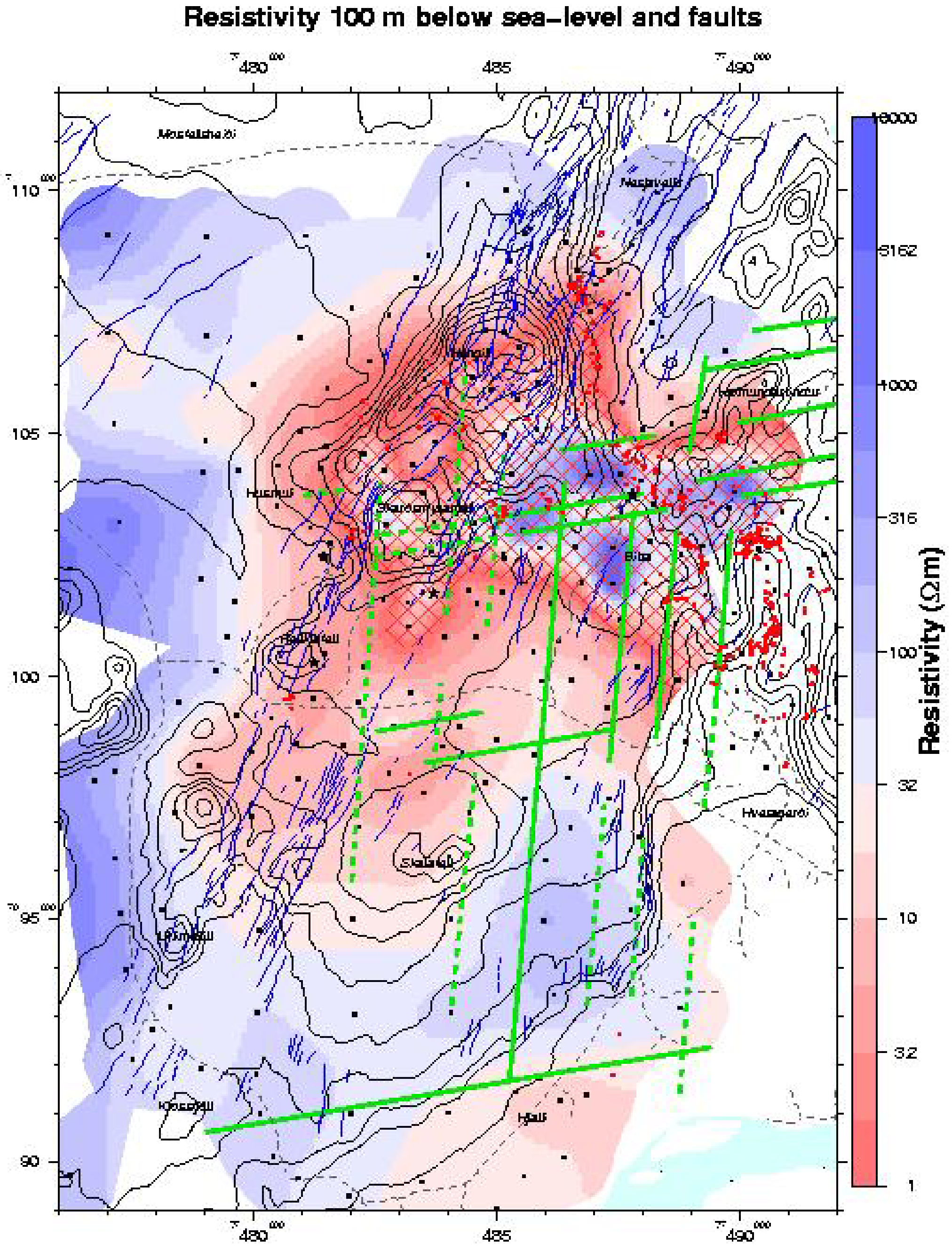


Figure 46. *Hengill area. Resistivity 100 m below sea level, faults and fissures (blue and green lines), surface manifestations (red dots) and wells south of Hengill (black stars).*

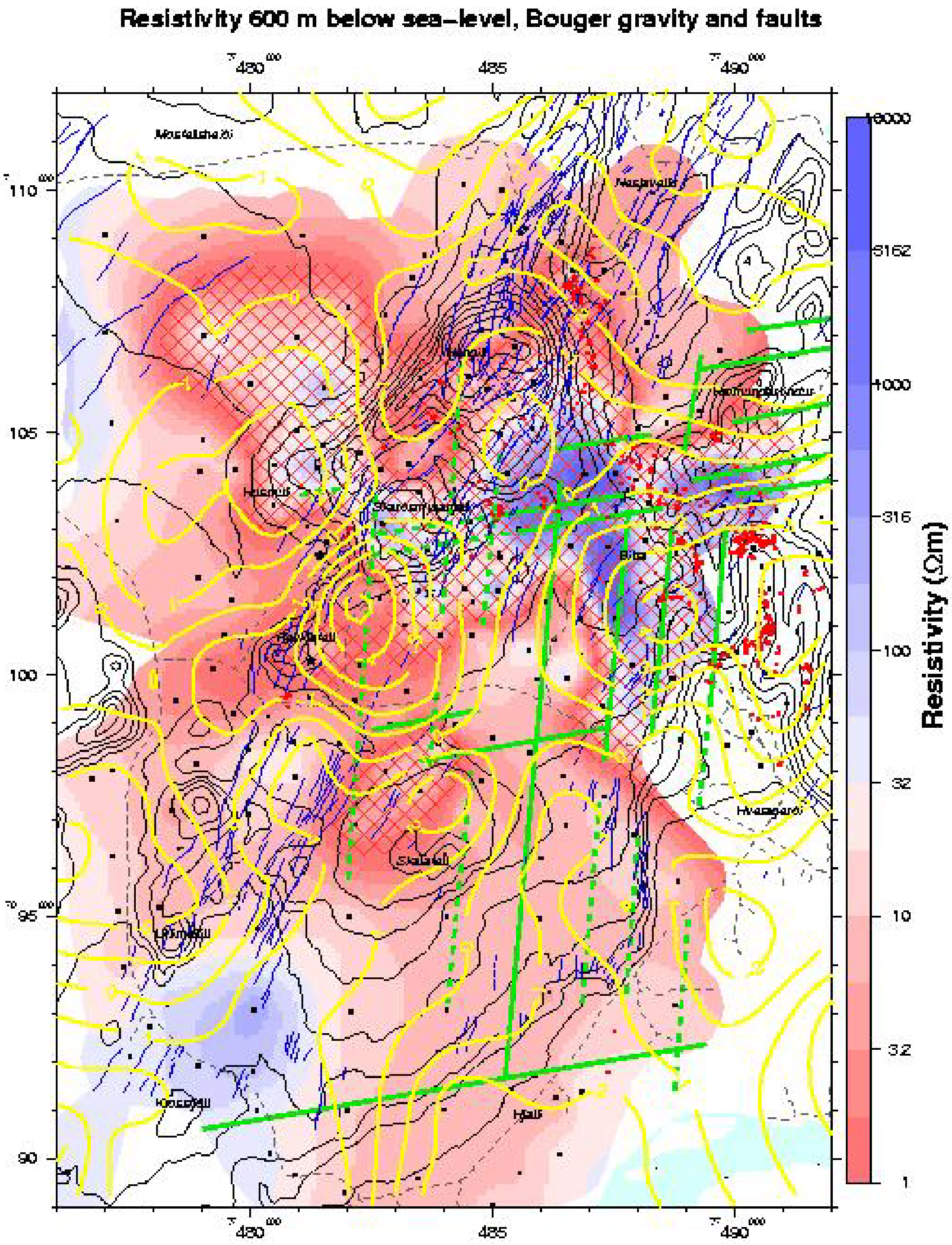


Figure 47. *Hengill area. Resistivity 600m below sea level, Bouguer gravity contours (yellow lines), faults and fissures (blue and green lines), surface manifestations (red dots) and wells south of Hengill (black stars).*

6.3 The Reykjanes Area

In 1996 a TEM resistivity survey was carried out in the western part of the Reykjanes peninsula. The survey covered an area extending from the shoreline in south and west to Kalmanstjörn in the north and Eldvörp high temperature area in the east. In addition a few soundings were carried out in the vicinity of Fagradalsfjall.

The survey reveals an extended high temperature field at Reykjanes as seen on a resistivity map, 700 meters below sea level, in Figure 8. The north-eastern boundary of the geothermal field is well defined but boundaries to south and west are off shore. The size of the geothermal field is therefore not known. The high-resistivity core reaches a height of -100 m (a.s.l) in the area where most geothermal manifestations are seen at the surface. From there it dips slightly towards south and west to about -300 m (a.s.l.) as far as it is possible to detect on land. Towards north and east the core dips steeply. A good correlation is seen between the resistivity structure and the thermal alteration derived from borehole data.

The resistivity structure at Sandvík, just north of the Reykjanes geothermal field, indicates high temperature alteration below -600 m (a.s.l.). The high-resistivity core reaches as high as -900 m (a.s.l.) where the temperature would exceed 250°C, provided there is equilibrium between thermal alteration and the present temperature state. That will however only be verified by drilling.

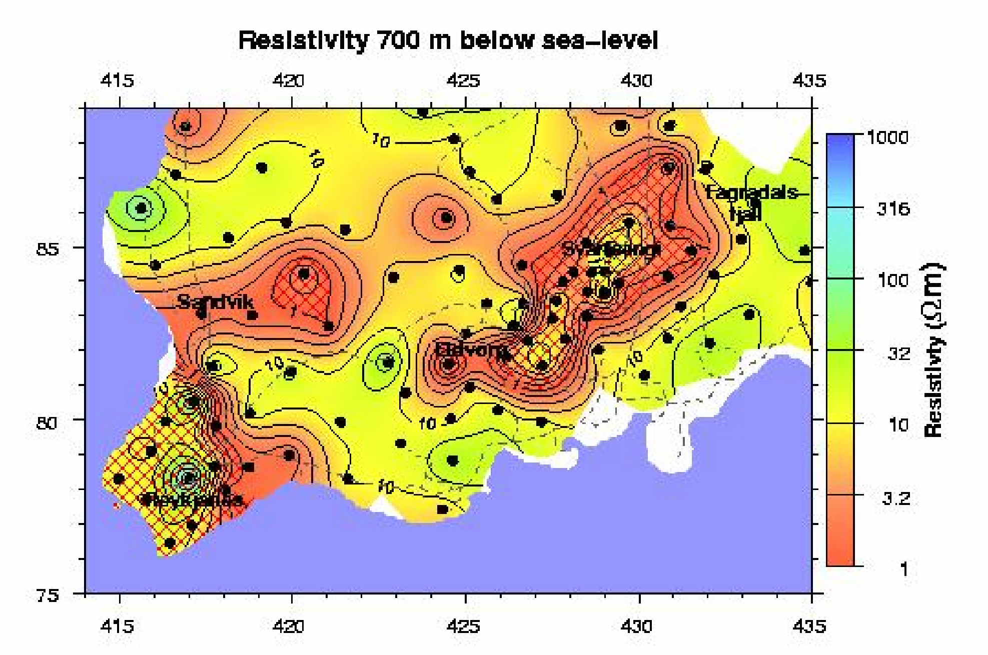


__Figure 48.__ Outer Reykjanes peninsula. Resistivity 700 m below sea level.

Reinterpretation of older TEM soundings from the Eldvörp geothermal field in view of the results from Reykjanes indicates strongly that Eldvörp and Svartsengi are one system. The high-resistivity core reaches height of -260 to -280 m (a.s.l.) with a thin overlying low-resistivity cap. The easternmost sounding shows the low-resistivity cap at the same depth as the mixed-layer-clay-zone is seen in borehole 9 in Svartsengi at a distance of 800 meters.

Seismic data allowing study of active tectonics like in the Hengill area, is not available at Reykjanes. The Reykjanes peninsula was very active seismically in the 1970's. Seismic data, on digital form, are, however, sparse from this period. Since then, the area has been very quiet, until recently. After the high seismic activity in the Hengill area, the activity has been increasing in the Krýsuvik-Trölladyngja area. This might indicate that increasing seismicity is to be expected further south on the peninsula in near future. The Reykjanes peninsula is now monitored by a relatively sensitive digital seismic network, operated by the Meteorological Office.

6.4 Krafla Area

Figures 49-52 show the resistivity structure in the uppermost one kilometre of the crust in the Krafla area. The results are mainly based on one-dimensional inversion of central-loop TEM data collected in 1991, 1993 and 1999. The data set is, in some cases, augmented by older Schlumberger and head-on-resistivity data.

Above sea-level, the results show three, largely separated anomalies of low resistivity which is under-lain by higher resistivity. The largest anomaly extends from Mount Krafla and its southern slopes and Kröfluháls in the south-east and to the north-west over Leirhnúkur and towards Hvannstóð. The eastern boundaries of the anomaly, north of Mount Krafla, are sharp and near vertical. The same applies to the south-west boundaries of the anomaly, under Grænagil, Leirbotnar and southern part of Leirhnúkur. They are sharp and near vertical down to sea level. Another resistivity anomaly is found under Leirhnúkshraun, west of the mountains Þríhyrningar, and extending to the south under Dalfjall. The third anomaly is under Sandabotnar and the southern part of Hágöng. At 200 m above sea-level, it connects weakly, west of Sandabotnar, with the anomaly under the southern slopes of Krafla. A part of this anomaly lies outside the caldera and extends outside the surveyed area so that its north-east boundaries are not defined. At sea-level, an anomaly starts to appear under the southern part of Sandabotnafjall and Sandabotnaskarð. At and right below sea-level this anomaly appears to be mostly separated from other anomalies.

The anomalies discussed above are thought to reflect, in some respect, distinct up-flow zones. At greater depths, the anomalies start to merge and at 400 m below sea-level, a continuous anomaly of high resistivity below low resistivity is observed, over an area of about 48 km^2. The resistivity soundings do not show signs of geothermal activity in a wedge into the main anomaly, under the valley Hlíðardalur and the western part Sandabotnafjall.

Contrary to what was expected, the resistivity soundings did not show resistivity anomalies below and south-west of Hvannstóð. It is generally believed that a geothermal system was active there, some thousand years ago. The observed resistivity structure does not indicate geothermal activity in this area, at present. The prominent and extensive resistivity anomaly under Hágöng was likewise unexpected. No indications of geothermal activity are found on the surface, but the anomaly has all the characteristics of a high-temperature geothermal system.

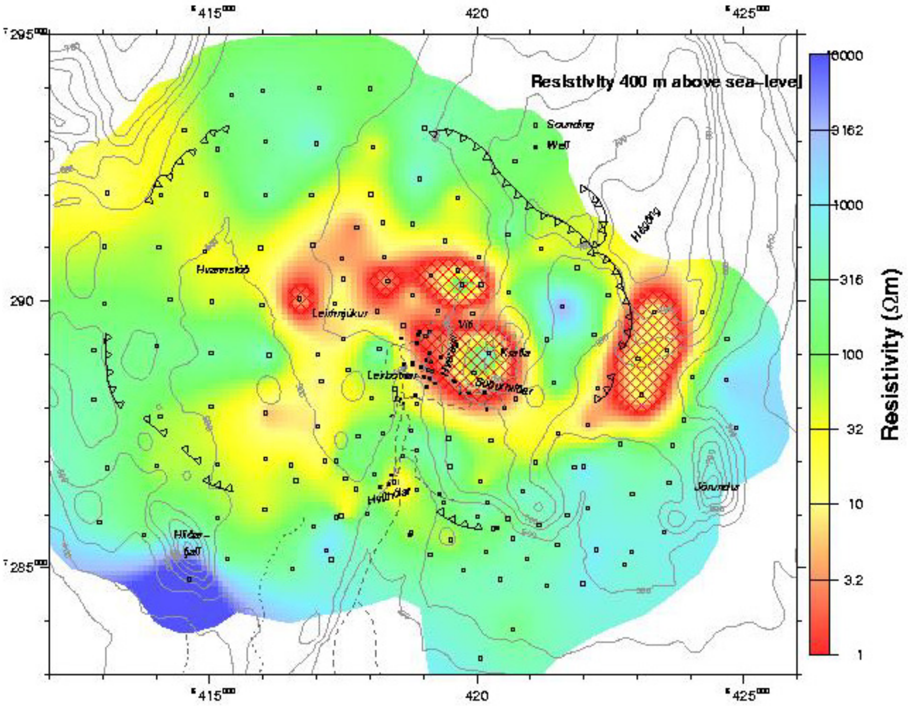


Figure 49. *Krafla area. Resistivity 400 m above sea level.*

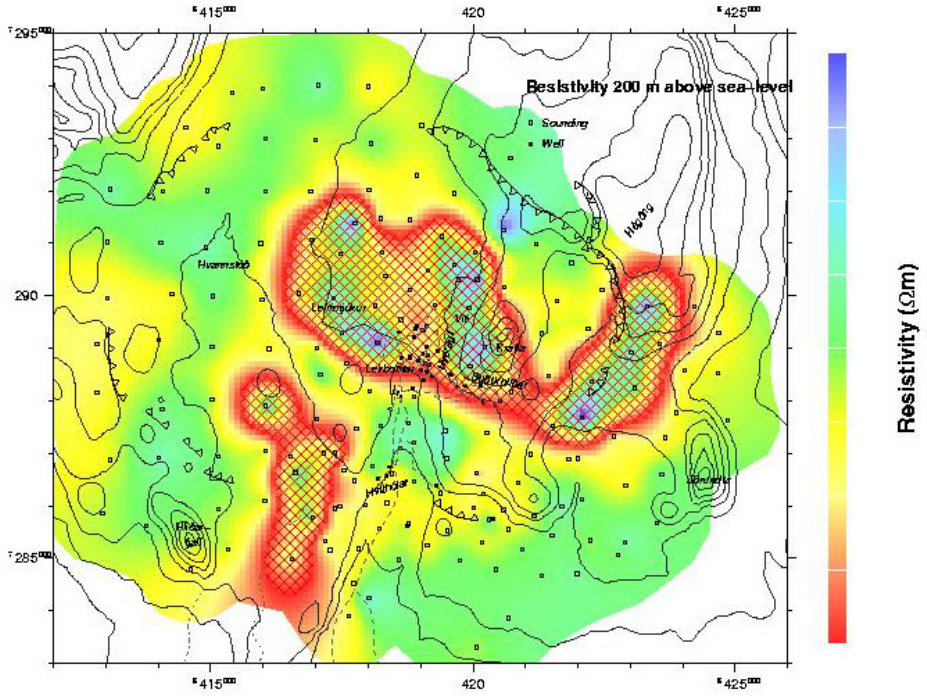


Figure 50. *Krafla area. Resistivity 200 m above sea level.*

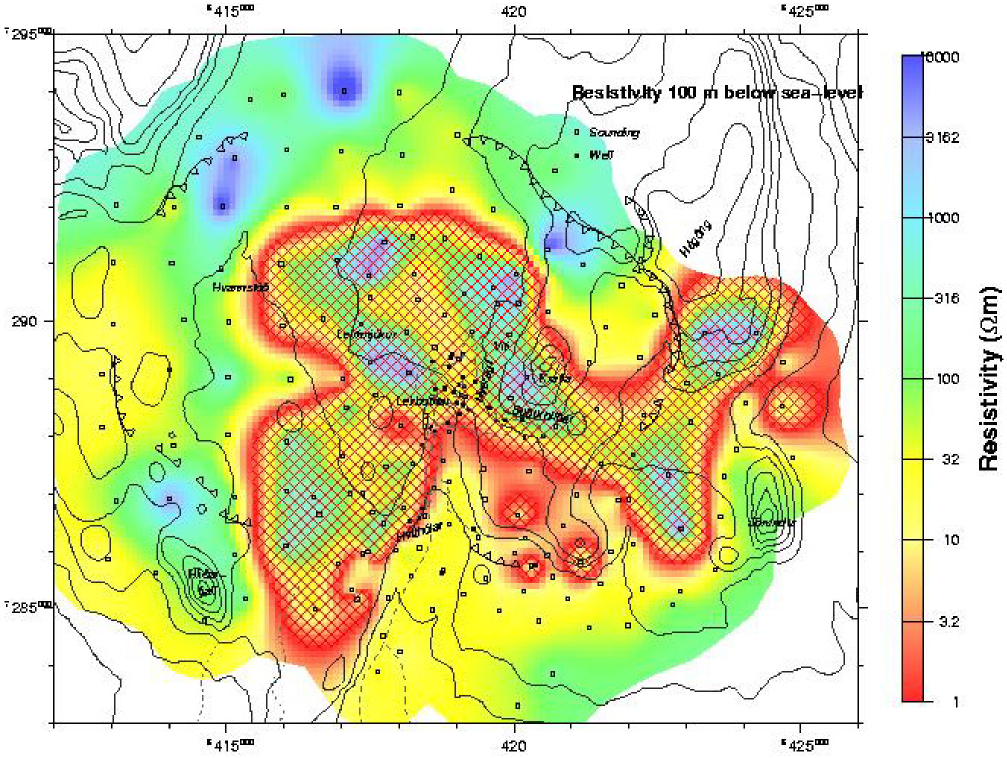


Figure 51. *Krafla area. Resistivity 100 m below sea level.*

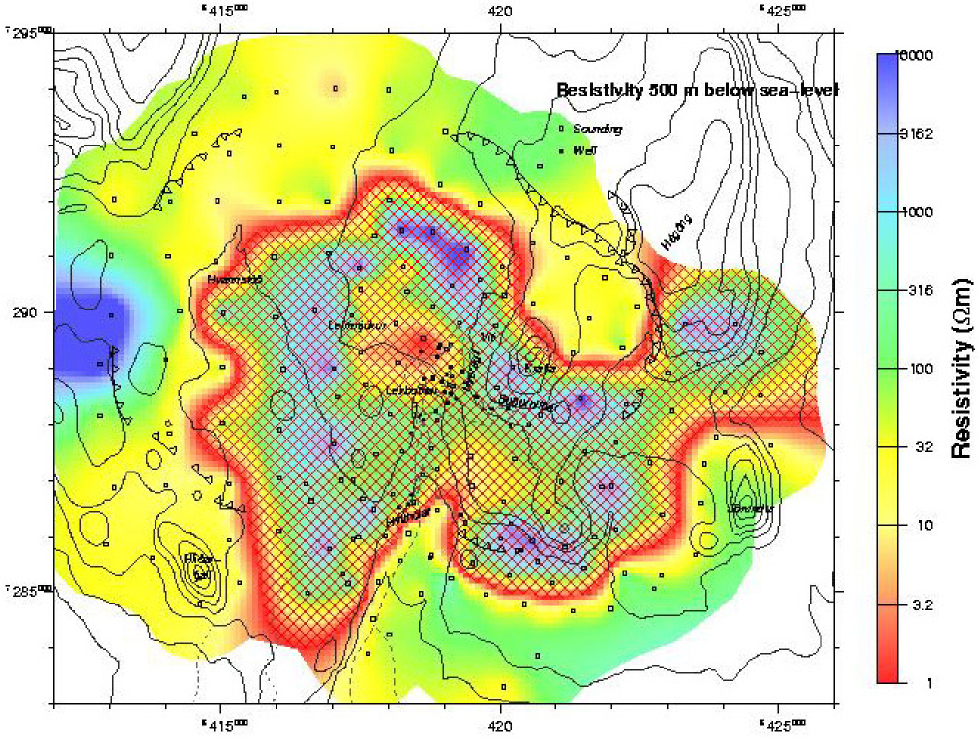


Figure 52. *Krafla area. Resistivity 500 m below sea level.*

6.5 Further Exploration

All the three geothermal systems which are considered as candidates for deep geothermal drilling have been studied in some detail, by TEM soundings, to a depth of about 1 km. Information on the shallow structure of the geothermal systems can, to some extent be extrapolated to greater depths, based on geological, geochemical and other geophysical data.

When wells are to be sited and drilled, aiming at targets in the depth range of 3-5 km, a more firm knowledge of likely conditions, than can be inferred from near surface data, is highly desirable. Such a knowledge can only be gained by geophysical methods. Of the available geophysical methods, resistivity and seismic methods have the highest potential for giving information on the thermal state at depth.

It is therefore suggested that deep resistivity surveys (probably MT), aiming at the resistivity structure in the depth range of 1-7 km, are conducted. In addition, it is suggested that the large earthquake data set from the Hengill area is analyzed, with the focus on lateral variations in the depth to the ductile-brittle transition, which is generally thought to be at temperatures of about 600-700°C. No extensive digital seismic data sets exist for the Krafla area nor for Reykjanes, but they may be accumulated in the future.

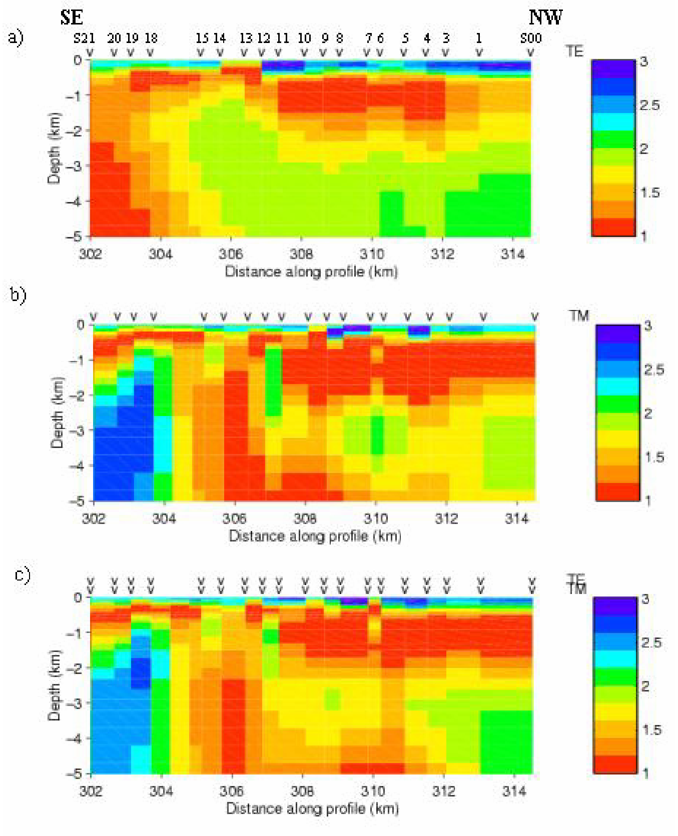


Figure 53. Models from 2D inversion of MT soundings along a profile in Threngsli, SW of Mt. Hengill. a) TE mode, b) TM mode c) TE and TM modes.

7 GEOPHYSICS 2 - SEISMICITY

In developed crustal genesis regions of Iceland, like at the proposed sites for the Iceland Deep Drilling Project (IDDP) at Reykjanes, Krafla and Hengill, it is hypothesized that the onset of semi-brittle state in crustal rocks occurs at the top of the lower crust. At approximately this depth does the frequency of earthquakes start to drop. It lies at 4-5 km depth under the IDDP sites. The depth above which 90 % of the seismicity lies, is defined as the depth to the brittle-plastic boundary and the bottom of the seismogenic part of the crust. This boundary lies between 6-7 km below the IDDP sites with a 1.5-2 km thick brittle-plastic transition zone above it. There are limited laboratory measurements available on rheology of basaltic rocks, but arguments exist for a 600°C temperature at the semi-brittle boundary and 760°C at the brittle-plastic boundary in a 2 cm/yr strain region like Iceland. These temperature depth values can be linearly connected from the surface with a thermal gradient between 110-130°C/km assuming approximately a 1.5 km thick transition zone. A 2 km thick brittle-plastic transition zone, however, suggests a decrease in thermal gradient in the top part of the lower crust compared to the gradient above. None-double couple earthquakes in the midcrust and in the top part of the lower crust in crustal genesis regions of Iceland do suggest that hydrous phases may exist in the crust at depths where the average temperature exceeds 400°C.

7.1 Introduction

The main motivation of the IDDP is research and application of geothermal energy at 4-5 km depth, with the aim of reaching a 400-600°C hot supercritical hydrous fluid (Fridleifsson and Albertsson, 2000). Three areas have been proposed as sites for this project, Reykjanes, Hengill and Krafla. The proposed 4-5 km drilling depth is double that of the deepest current geothermal wells in Iceland. The most relevant information on physical conditions for this project is rock temperature and concentration of chemicals in liquid, and pressure at 4-5 km depth in the high temperature geothermal fields of Iceland. Here it will be examined what contribution seismology can make and has made to predict the temperature and liquid concentration at 4-5 km depth in a high energy geothermal environment. As this project will enter a new geological frontier it is very important to maintain a broad research view that can aid future projects of similar type. A very important objective for that view is that the proposed hole should penetrate into the lower crust.

Seismology can give an indication of liquid concentration in a rock mass (water, magma, oil or gas), but seldom a direct proof except in extreme cases. One method for such an exploration, is to measure the ratio of compressional velocity over shear velocity (v_P/v_S) , or another combination of these velocities called the Poisson's ratio. Subsurface hydrous phases are among factors that can lower this ratio (Nur, 1987), but porosity and fracture geometry can have a similar effect. The existence of a partial melt within a rock mass has the opposite effect of water in that it increases the v_P/v_S ratio. Melt can have a wide distribution, especially in the mantle. However, water saturation in a rock mass is usually on such a small geological scale, a few kilometers or less, that it is only detected with high resolution measurements of the velocity structure. High resolution measurements are costly and not as common as the lower resolution measurements. The Hengill area is the only one of the three proposed drill sites where such a survey has been carried out (Foulger et al., 1995). Its reults showed a decrease in the v_P/v_S ratio in the top 3 km of the crust that correlates closely with areas of hot springs and fumaroles, and was interpreted as a hydrous effect on the v_P/v_S ratio.

The other seismological indication of fluids within the crust comes from the existence of non-double couple earthquakes of explosion or implosion type. They have been observed both in the Krafla and Hengill areas (Foulger, 1988; Foulger et al., 1989). The most recent and comprehensive study in the Hengill area, resulted in the location of six non-double couple earthquakes in the depth range 2.9-5.0 km during one summer recording (Julian et al., 1997). Five of the six were of explosion type. No non-double couple earthquakes have been documented on the Reykjanes Peninsula, but not much effort has been put into looking for them there.

There exist abundant low resolution (1/2-10 km depth and 5-50 km lateral resolution) refraction measurements of the Icelandic crust, a couple of those close to the proposed IDDP sites. These measurements yield the one or two dimensional absolute body wave velocity of the crust, always compressional velocity and sometimes shear velocity as well. Though the direct temperature effect on seismic velocity is rather low, except close to the solidus (Sato et al., 1989), it will be argued in this report that even a low resolution knowledge of the crustal structure can be crucial to put bounds on the thermal state of the crust, with perhaps 100°C uncertainty in temperature at 5 km depth. The primary link between seismic velocity and temperature that will be emphasized here, comes from correlation of seismic velocity with the thickness of the seismogenic zone (i.e. the brittle part of the crust).

It is concluded that a reasonable estimate can made of the temperature of the crust at 5 km depth below high energy geothermal fields in Iceland. However, detection of hydrous fluids with seismic imaging techniques requires more detailed knowledge of the velocity structure than is generally available in Iceland, and may need more development before they can be used for deep geothermal exploration. The occurrence of explosive non-double earthquakes down to 5 km depth in the volcanic rift zones of Iceland does suggest existence of fluids down to that depth.

7.2 Crustal velocity structure of Iceland

The Icelandic crust is created in the on land portion of the Mid-Atlantic ridge. The wave speed of the crust in Iceland corresponds closer to wave speeds observed in oceanic crust than in continental crust (Pálmason, 1971; Bjarnason et al., 1993). The similarity in wave speed suggests similarity in the chemical composition of basaltic type, which is certainly observed in the surface geology (Sæmundsson, 1979). On the other hand the thickness of the crust in Iceland resembles more closely the thickness of continental crust. The thickest Icelandic crust is 30-40 km thick (Stables et al., 1997; Menke et al., 1988; Darbyshire et al., 1998; Du and Foulger, 2001) and probably covers more than half the island (Bjarnason and Sacks, 2002). The thinner part of the Icelandic crust is between 15-24 km thick (Bjarnason et al., 1993; Brandsdóttir et al., 1997; Weir et al., 2001). As a consequence of the thick Icelandic crust, crustal velocity gradients are considerably lower in Iceland than below the oceans.

In Iceland as elsewhere the crust is divided into two parts, the upper and lower crust, also called layers 2 and 3 (Pálmason, 1971). This division is best defined as occurring at a significant change in the velocity depth gradient, a change of the order of a magnitude in the Icelandic crust (Flóvenz, 1980). This division usually also occurs close to the depth of the 6.5 km/s compressional velocity, which is defined to be the boundary velocity between the upper and lower crust (Pálmason, 1971). The thickness of the upper crust varies between 3-10 km (Flóvenz and Gunnarsson, 1991), and that of the lower crust by 10-30 km. The thickness of the upper crust in the neovolcanic zones of Iceland is between 3.5-6.5 km thick (Bjarnason et al., 1993; Brandsdóttir et al., 1997; Darbyshire, et al., 1998; Du and Foulger, 2001).

Lately the upper crust has been divided into an upper and lower part in Iceland. The upper part, still called upper crust, and the lower part called midcrust (Bjarnason et al., 1993; Darbyshire, et al., 1998). This distinction is geologically useful in associating the upper crust with mostly extrusive basaltic rocks with similar velocity as the oceanic layer 2A (3.0-5.5 km/s). The midcrust consists likely of increased volume of intrusives and metamorphosed basalts as observed in ophiolites with a velocity range of oceanic layers 2B and 2C (5.5-6.5 km/s) (Bjarnason et al., 1993. Note a change from Bjarnason's et al., (1993) definition of 5.0 to 5.5 km/s for the upper and midcrust boundary). The velocity depth gradient of the midcrust is usually 3-4 times lower than the upper crustal gradient and 5-6 times higher than the lower crustal gradient. The midcrust therefore has several intermediary properties of the upper and lower crust including, velocity, velocity gradient and degree of instrusives and metamorphism. This tripartite division of the crust will be followed in this report.

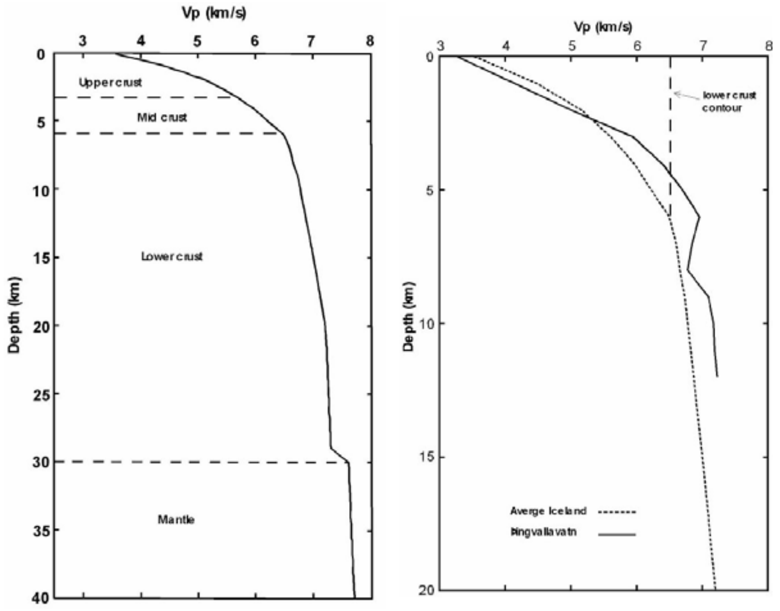
Figure 54a shows a smooth one dimensional compressional velocity model that demonstrates the tripartite division of the crust and is probably a good average crustal compressional velocity model for Iceland. Its upper 20 km part was compiled by Bjarnason et al. (1993) for the South Iceland Lowlands and is the standard model used for earthquake location in Iceland by the Meteorological Office (the SIL model). Here it has been extended to 30 km depth to represent the average thickness of the Icelandic crust. The depth to the lower crust is 6 km, with 2.7 km thick upper crust and 3.3 km thick midcrust. In comparison Figure 54b is an un-smoothed one dimensional compressional velocity model for the Þingvallavatn area, 5 km north of Hengill. This model may be more representative for the velocity structure of the candidate IDDP sites. It has a 2.5 km and thick upper crust and a a 1,9 km thick midcrust with 4.4 km depth to the lower crust. Here there is a smaller difference between the velocity depth gradients of the upper and midcrust than usually. Notice the 2-3 % velocity inversion at 7-9 km depths. It compares to a hypothesized magma inflation at 7 km depth, the source of crustal deformation near the Hengill volcano in 1993-1998 (Feigl, et al., 2000).

7.3 The seismogenic crust and temperature

Stefánsson et al. (1993) found a remarkable deepening of the seismogenic (brittle) crust from the Western Volcanic Zone (WVZ) in the Hengill area east along the South Iceland Lowlands (SIL) towards the younger Eastern Volcanic Zone (EVZ) (Figure 55). Comparing the Stefánsson et al’s. (1993) finding with the relatively high resolution velocity structure measured on the SIST tomographic refraction profile that passed over this area (Bjarnason et al., 1993), it is observed that the brittle-plastic boundary (defined as the depth above which approx. 90 % of microseismicity lies) correlates with the 6.75 km/s compressional velocity contour. Likewise, if the semi-brittle or the brittle-plastic transition zone is defined to lie between the depth where microseismicity has declined by 1/3-1/2 from its maximum depth frequency and the 90\% accumulated microseismicity, a correlation is observed with the onset of semi-brittle state and the depth to the lower crust, the 6.5 km/s compressional velocity contour. It is therefore postulated here that the compressional velocities 6.5 km/s and 6.75 km/s are important rheology and temperature markers within the crustal genesis zone and some spreading distance away from it. From the WVZ into the SIL region this correlation holds to approx. 7 Ma.

Within the framework of Pálmason's (1986) crustal formation model a boundary like the mid-lower crustal boundary is advected to greater depth with time, but reaches a maximum advection depth some distance away from the axial rift zone. However, the isotherms continue to deepen away from the axial rift zone unless a new thermal source lifts them up. Crustal erosion also moves the markers closer to the surface and they cool faster. The 6.5 km/s and 6.75 km/s markers therefore do not define uniform rheological properties for the whole of Iceland.

There is a lack of laboratory rheology measurements of basaltic rocks. Bjarnason et al., (1994) estimated from limited data a temperature range 600-700°C, or an average 680°C, in the brittle-plastic transition zone within a 2 cm/yr plate velocity zone as in Iceland. Assuming a linear temperature gradient and a 680°C temperature in the middle of the transition zone, a temperature can be calculated at the onset of the transition at the mid-lower crustal boundary. Such a calculation e.g. for the Þingvallavatn area (Figure 54 b) gives the temperature 620 +/-90°C at the mid-lower crustal boundary at 4.4 km depth and a thermal gradient of 140 +/- 20°C/km.



a) **b)**

Figure 54 ***a)*** *A tenable average compressional velocity structure for Iceland showing the tripartite division of the crust into an upper, middle and lower part. The top 20 km is the SIL model extended to 30 km thick crust with a small crustal-mantle velocity discontinuity.* **b)** *The compressional velocity in the Þingvallavatn area, 5 km north of Hengill on the SIST profile on top of the average Iceland model. Notice the velocity inversion at 7-9 km depth in the Þingvallavatn model, which coincides with proposed magma inflation depth during the 1993-1998 Hengill uplift period (Feigl, et al., 2000).*

7.4 Temperature at 5 km depth in crustal genesis regions

Of the three proposed IDDP sites Reykjanes is the only one where an undisturbed geothermal gradient has been determined locally in an 800 m deep hole (Orkustofnun database). The temperature-depth profile is highly linear with a gradient 115°C/km (Figure 56). A linear extrapolation of these measurements gives a temperature of 575°C at depth 5 km depth. This hole is located in Miðnessheiði, 15 km from the main geothermal fields at Reykjanes and may therefore reach a cooler crust.

A high resolution (within ¼ km) determination of the depth to the lower crust, the important rheology marker, has not been carried out at any of the IDDP sites. Brandsdóttir et al. (1997) determined the velocity structure of the top 2 km within the Krafla caldera with high depth resolution, but the deeper structure is mostly modelled by large offset (>50 km) undershooting measurements. The depth to the lower crust is modelled in the range 3-4 km within the Krafla caldera and magma storage region at 3-4.5 km depth (Figure 57) was imaged too. A number of reversed medium resolution refraction profiles were obtained for the Reykjanes peninsula (Pálmason, 1971). Flóvenz (1980) reanalyzed these measurements and determined a 4.3-4.5 km depth to the lower crust (layer 3). The present author recommends that these data should be further analyzed and augmented by reading all seven recording channels instead of just the one that Pálmason's (1971) and Flóvenz (1980) analysis are based on, given that the channel spacing can be sorted out. The recent Reykjanes-Iceland Seismic Experiment (RISE) (Weir et al., 2001) added little new information on the crustal structure of the upper and midcrust on the Reykjanes Peninsula due to a lack of on land sources and receivers. They modelled a 4.0 km depth to the lower crust at the Reykjanes. No high resolution refraction has been run directly across the Hengill area, but such a profile has been measured 5-10 km north of the Hengill geothermal region (Bjarnason, et al., 1993), and a 4.4 km depth to the lower crust observed (Figure 54b). There may be an uncertainty of approx. one kilometer in the estimated lower crustal depths at all three IDDP sites (Table). It is also possible that there is up to one kilometer variation in the estimated lower crustal depth within individual regions, as a result of up-doming of the lower crust within central volcano areas.

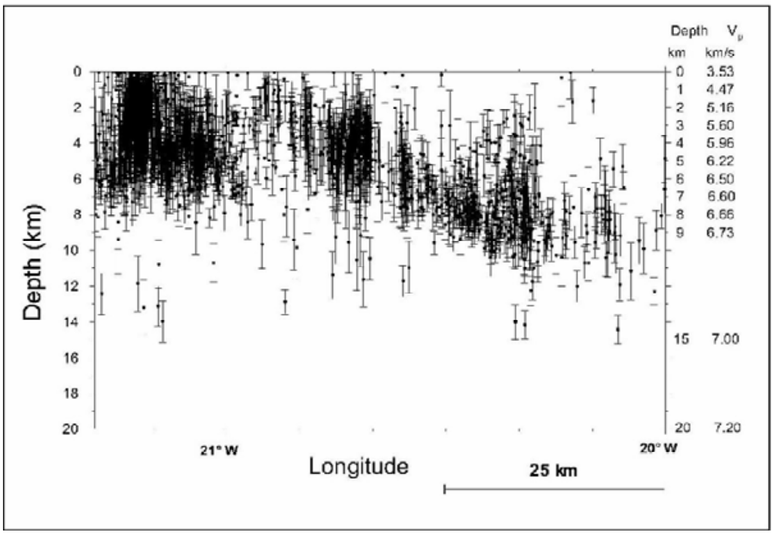


Figure 55. *Depth of earthquakes versus longitude inside the South Iceland Lowlands into the Western Volcanic Zone recorded on the SIL network from 1. July 1991 to 31. December 1993 by the Icelandic Meteorological Office (Gunnar Guðmundsson, personal communication, 2002). The SIL compressional velocity model used to locate the earthquakes is shown on the right. Notice the deepening of the seismogenic thickness from approx. 6 km at the western end to approx. 11 km at the eastern end.*

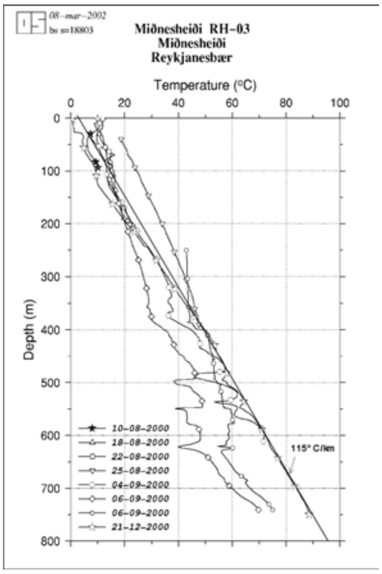


Figure 56. Temperature depth profile on Miðnesheiði at the western end of the Reykjanes Peninsula. Different symbols represent measurements at different times. The latest measurements (star symbol) show a highly linear profile with a thermal gradient 115°C/km (From the Orkustofnun database).

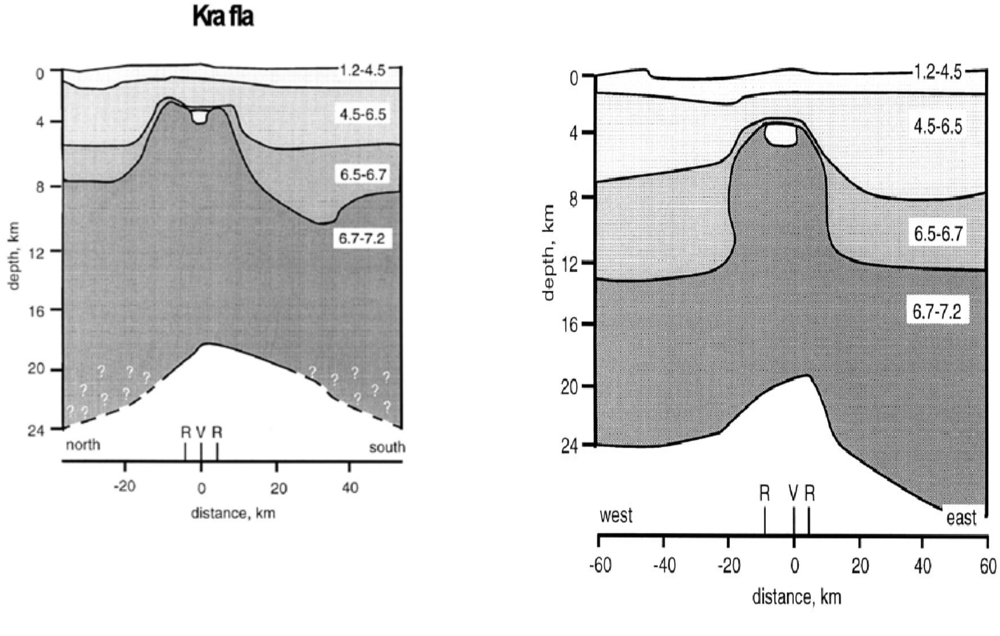


Figure 57. *North-south and east-west compressional wave speedcross section of the Krafla area (Brandsdóttir et al., 1997). The Rand V labels on the lateral scale position the caldera rim and the caldera lake named Víti. The lower crust rises to 3-4 km depth under the Krafla volcano with a magma storage region at 3-4.5 km depth, shown with lighter shading.*

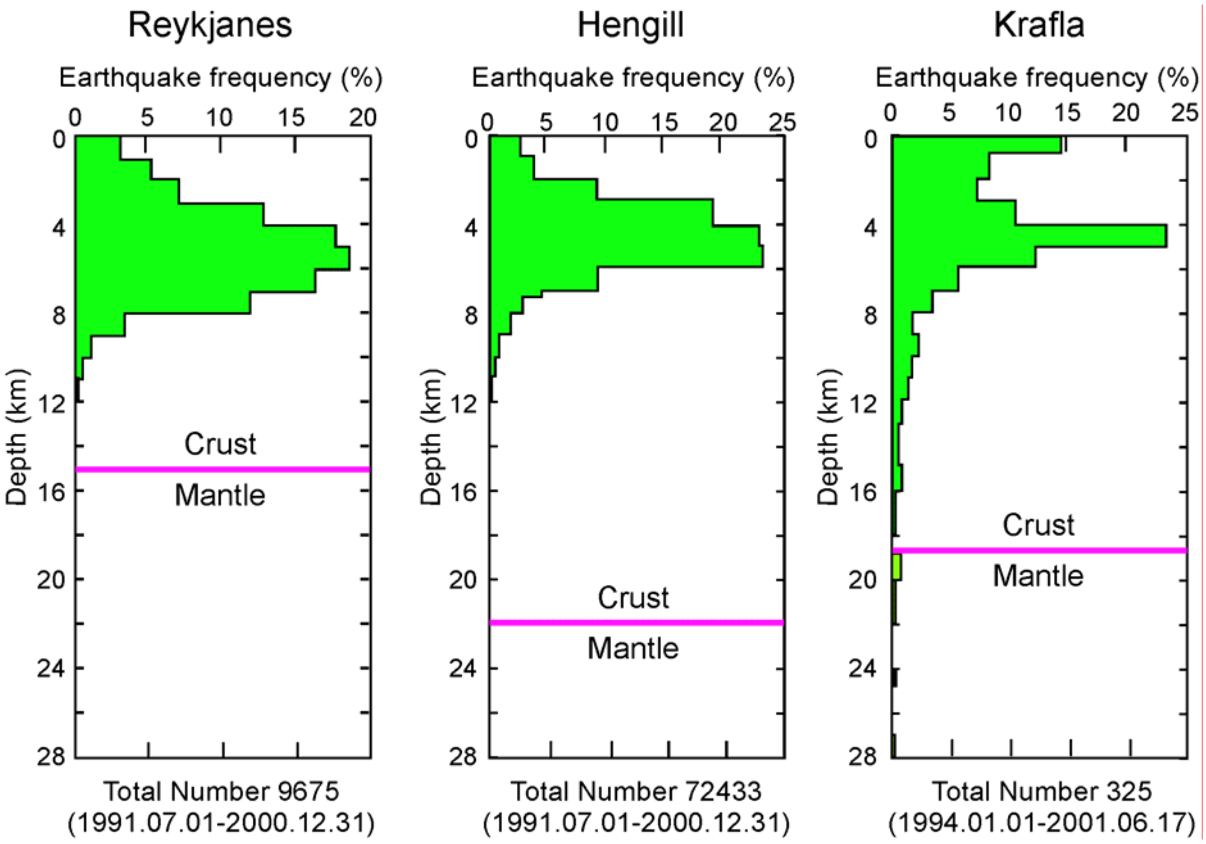
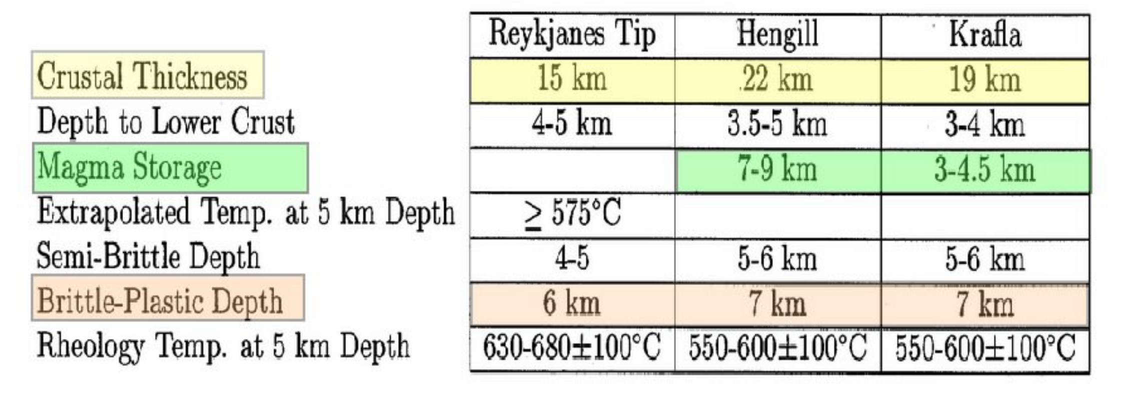


Figure 58. *Earthquake depth frequency on the Reykjanes Peninsula, Hengill and Krafla areas recorded by the Meteorology Office (Guðmundsson et al., 2001). The arrows give the approx. depth of the accumulated 90 % of the seismicity measured from the surface, which is defined as the brittle-plastic boundary. Notice the sharp drop in seismicity around this boundary on Reykjanes and Hengill, suggesting a high thermal gradient.*

The thickness of the seismogenic crust, that may correspond to a bottom temperature of 760°C, is reasonably well determined at all three IDDP sites. The onset of the semi-brittle zone, that may correspond to a temperature of 600°C is less well constrained. The Krafla and Hengill areas both have a 7 km thick seismogenic crust (Figure 58; Guðmundsson et al., 2001). The average seismogenic thickness in the Reykjanes Peninsula is 8~km (Figure 57), but thins towards the west and is 6 km thick at the tip of the peninsula (Klein et al., 1973; Guðmundsson personal communication, 2002). Based on seismogenic thickness alone, Reykjanes is the hottest of the three locations. If we assume a 1.5 km thick transition zone at all three sites, then we can linearly connect the transition zone temperatures with a surface temperature and thermal gradients between 110-130 °C/km. This gives the lower rheology temperature at 5 km depth in the Table. If, however, we assume a 2 km thick transition zone, then the thermal gradient is lower in the transition zone than above it. This gives the higher rheology temperature at 5 km depth in the Table. It is worth noting that the thermal gradient measured on the western part of the Reykjanes Peninsula (Miðnesheiði) is almost the same as that obtained from the estimated rheology temperature in Hengill and Krafla, but 9-15 % lower than estimated rheology temperature for Reykjanes (Table 8). As was pointed out before the higher calculated rheology temperature may be real, because the borehole is 15 km outside the high temperature geothermal area.

There are a number of uncertainties in the seismogenic thickness determinations, which may be of the order of one kilometer at the IDDP proposed sites. The seismic network of the Meteorological Office has only been dense enough for good hypocenter depth determination since 1997 on Reykjanes. From that time Reykjanes has been almost aseismic. However, combining the limited Meteorological Office data since 1997 with the portable network of Klein et al. (1973), a coherent picture emerges. The Krafla area has not been very active seismically since 1994 when recording by the Meteorological Office started in north Iceland. For that reason the hypocenter depth distribution may still be a little uncertain and the estimated deeper seismicity questionable. The seismogenic thickness of the Hengill area may be overestimated by about 1 km due to the increased strain rate in 1993-1998.

Table 8. *Results of the study of seismicity.*



	Reykjanes Tip	Hengill	Krafla
Crustal Thickness	15 km	22 km	19 km
Depth to Lower Crust	4-5 km	3.5-5 km	3-4 km
Magma Storage		7-9 km	3-4.5 km
Extrapolated Temp. at 5 km Depth	≥ 575°C		
Semi-Brittle Depth	4-5	5-6 km	5-6 km
Brittle-Plastic Depth	6 km	7 km	7 km
Rheology Temp. at 5 km Depth	630-680±100°C	550-600±100°C	550-600±100°C

8 ENVIRONMENTAL ISSUES

8.1 Legislation

According to the Act on Environmental Impact Assessment, No. 106/2000, all projects, which may have a significant effect on the environment, natural resources or community, shall be subjected to an Environmental Impact Assessment (EIA). Skipulagsstofnun, the Planning Agency, monitors the application of law and regulations on planning, building and Environmental Impact Assessment. The Minister for the Environment has the supreme control of planning and building under the Planning and Building Act and EIA programmes under the Act on Environmental Impact Assessment. The assessment must be a part of the planning process.

A regulation supplementing the environmental act states which projects are compulsory for an EIA. Other projects, which may or may not be subjected to an assessment, depending on their magnitude, are listed in Appendix 2 of the regulation. It includes “*drilling of production wells and exploration wells in high enthalpy fields*”, and “*plants for production of electricity, steam and hot water, hydro plants with installed capacity of 100 kW or more or geothermal exploitation of 2500 kW or more*”. Apparently the IDDP falls under projects listed in Appendix 2. In such cases the executing party prepares a report, the Environmental Impact Statement, to inform the Planning Agency of the intended project. The report must include a detailed description of the proposed project, in accordance with the procedure outlined in the regulations. After evaluation the Agency makes a decision on whether the project is exempted from EIA.

Figure 59 shows the Environmental Impact Assessment process from the initial notification of the project and scoping of the assessment to the final ruling by the Planning Agency or the minister for the environment, in case the Planning Agencies ruling has been appealed. This process is described in further detail in chapter 14 (Environmental Impact of Drilling) in Part II.

8.2 Geothermal experience

Initial development of the three geothermal fields in question, i.e. Reykjanes, Hengill and Krafla, predates the present environmental act and the request for a modern EIA. But in recent years additional development in all these fields has been subjected to such a study, and it is useful to analyse the resulting environmental reports in order to foresee what will be the main environmental concern resulting from a deep drilling project in one of the three areas. In some cases it has been a complete Environmental Impact Report, but in other cases projects under Appendix 2 as described above have been considered

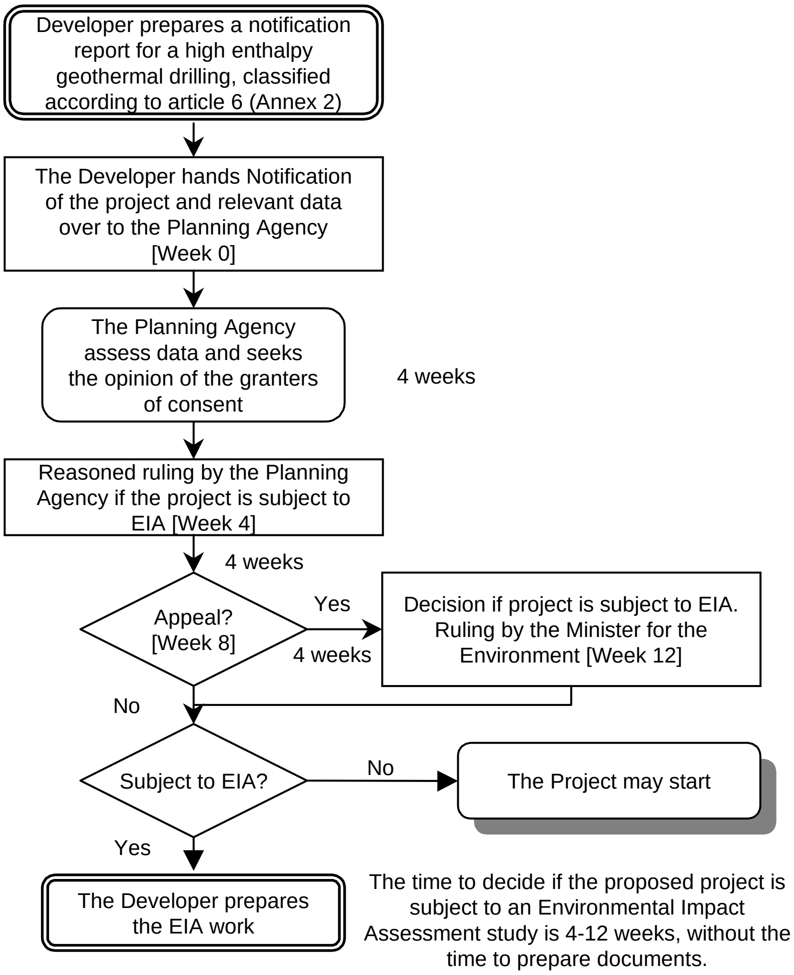


Figure 59. *The process from the notification of a high enthalpy geothermal drilling project, leading to the decision if the project is subject to Environmental Impact Assessment or not.*

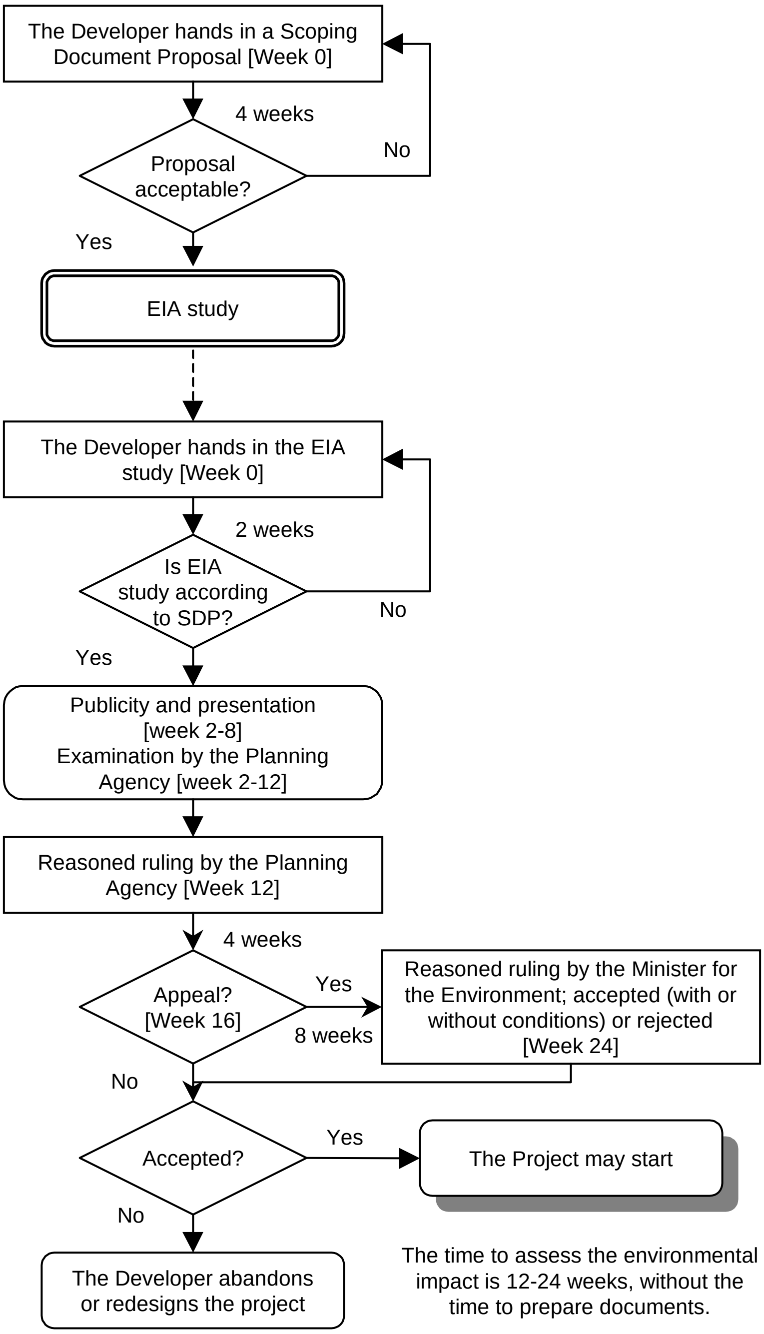


Figure 60. *The process of an Environmental Impact Assessment study, from the scoping of the EIA-Report to the ruling of the Minister for the Environment.*

8.3 Reykjanes

Geothermal steam has been used at the Reykjanes Geothermal Area for extracting salt from the geothermal brine. Currently, the factory produces high quality salt called "Edalsalt" and exports about 150 tonnes per month to the UK. Process steam produced is 16 kg/s. The plant also produces electricity, 0.5 MW_e, for its own use.

In 2000 Hitaveita Suðurnesja submitted an Environmental Impact Statement to the Planning Agency on a proposed industrial development at the Reykjanes high enthalpy field (VSÓ 2000). The project involved drilling for sufficient steam for a 100 MW_e power plant, estimated 18 production wells, 11 exploration wells and 5 reinjection wells.

In March 2000 the Planning Agency published its decision on the Environmental Impact Statement. Drilling is permitted within the planned industrial area, but additional assessment is required on several listed items:

1. Disposal of wastewater. A study of the effect of dilution of sea water on the flora and fauna at the proposed location of disposal,
2. A study of the flora and the fauna in the dilution area,
3. Further information on the concentrations of dissolved solids in the wastewater and their influence on the marine biosphere, such as silica, aluminium, iron, and manganese as well as various heavy metals such as cadmium, copper and zinc as well as arsenic and lead.
4. Information on flora and fauna within the proposed reinjection area and an evaluation of the adverse influence caused by construction of roads, pipelines, drilling platforms etc.

The developers disputed the verdict but the Minister of Environment confirmed the Planning Agencies ruling.

In July 2002 a new plan was presented to the Planning Agency (VSÓ 2002) involving 7 production wells within the planned industrial area, 3 reinjection wells and 3 exploration wells outside the planned industrial area. In September 2002 the Planning Agency issued a ruling where the plan was agreed upon with a few mitigating measures regarding disposal of geothermal brine.

8.4 Hengill

Four high enthalpy geothermal fields, i.e. Hveragerði (including Grændalur), Ölkelduháls, Nesjavellir and Hellisheiði have developed within central volcanoes in the area. Environmental Impact Statements have been prepared for proposed development in the three first named fields within the last 8 years, and EIA is being prepared for the last one.

Nesjavellir

The construction of the geothermal power plant at Nesjavellir predates the requirement for EIA. The permit obtained at the time allowed the drilling for water and steam sufficient for the production of 400 MW_t and 76 MW_e. In the late 1990s plans were made to increase the power production at Nesjavellir to 90 MW_e, and Orkuveita Reykjavíkur submitted an Environmental Impact Statement (VGK 2000) to the Planning Agency. After reviewing the statement the agency issued its decision in January 2001. In general the statement was accepted without any additional conditions, but the main concern in the agency’s report is the disposal of brine and condensate from the boreholes and the power plant. The mitigation measures proposed by the operator in the Environmental Impact Statement, involving reinjection, are supported by the agency.

In July 2002 Orkuveita Reykjavíkur submitted an Environmental Impact Statement for expansion from 90 MW_e to 120 MW_e at Nesjavellir. The statement was accepted by the Planning Agency in September 2002.

Ölkelduháls

Prior to the drilling of one geothermal well in 1995, no development had taken place in the Ölkelduháls field. Hitaveita Reykjavíkur (later Orkuveita Reykjavíkur) had carried out a surface reconnaissance project, and in 1995 the first (and so far the only) exploration borehole was designed and sited. An Environmental Impact Statement (Gunnlaugsson 1994) was prepared and delivered to the Planning Agency for evaluation and decision. The main comment from the agency concerned the construction of a road to the Ölkelduháls area. The area did not have any road connection except for a simple track for four-wheel drive vehicles. The construction of a 5 km long road to bring a drilling rig into the area was proposed in the statement. The Planning Agency accepted this plan, but put stringent restrictions on design, material etc. Requirements regarding disposal of waste products during drilling and well testing were spelled out.

Grændalur, Hveragerði

The Hveragerði high enthalpy field is partly located within the township of Hveragerði and partly in the slopes of the mountains north of the town. Drilling for steam in the town of Hveragerði started as early as 1947, and the steam has been used for industry, mainly for the extensive greenhouse industry. Considerable exploration has been carried out in the Hveragerði area, and apparently the main upflow area is in Grændalur on the slopes north of Hveragerði. Plans were made by the firm Sunnlensk orka to investigate the reservoir of the Grændalur field by deep drilling. In an Environmental Impact Statement (VGK 2000b) four drill sites were considered (Figure 61), one at the mouth of the Grændalur valley (location a), one right in the center of the valley, close to the river Grændalsá (location b), one on the slopes north of the bottom of the valley, close to Ölkelduháls (location c) and one on the eastern slope of the valley (location d). Exploration results suggested that location b was the most promising, locations a and especially d were less promising but less was known about the possibilities of location c. There is a road connection to location a but not to the others. A one km track would be needed to reach site c from the road accompanying the electric line to the Búrfell power station. The Planning Agency accepted the drilling for location a, but rejected all plans for constructing a road into the Grændalur area and drilling in locations b or c. The decision to turn down the request for drilling in Grændalur was based on:

1. **Road construction**. No roads or tracks exist in the Grændalur valley. At least four options for a road location were proposed in the statement, but the agency considered that all of these would cause irreversible damage to the environment, especially the main spring and fumarole areas. Due to the steep slopes any road construction in this area would create an eyesore in the unspoiled landscape.
2. **Tourism and hikers**. It is pointed out that Grændalur is a popular unspoiled hiking area close to the main population centers of Iceland. Numerous hot springs, colourful rock formations and vegetation makes this area unique for outdoor activities, and the Agency considers that the proposed drilling and related activities would greatly reduce the value of the Grændalur for hiking and other outdoor activities.

Figure 61. *Hveragerði area. Proposed drillsites in Grændalur shown.*

It should be pointed out the Agency considers that drilling and well testing as such would not have serious influence on the area and its flora and fauna.

The potential operators of the field, Sunnlensk orka, were not satisfied with the decision and complained to the Ministry of the Environment who is the final arbiter in such cases. Their demand was that the decision of the Planning Agency be reversed and drilling at site b be permitted but if this permit were not granted that drilling at site c be permitted. The final outcome was that the Ministry has granted permission for drilling at site c provided that the track needed would follow the contours of the landscape and that excavation for material be carried out in cooperation with the Nature Conservation Agency.

Hellisheiði

The first deep drilling at the Hellisheiði geothermal field in 1985 predates the Environmental Act, but since 2001 Orkuveita Reykjavíkur has drilled five deep exploration wells in the area. The drilling was reported to the Planning Agency according to Appendix 2 of the Environmental Act. The field is a popular area for outdoor activities, both in summer and winter, due to its scenic landscape and proximity to the capital. Three large power lines cross the area, and all the locations for the boreholes were close to existing roads, therefore a minor surface disturbances were caused. The Planning Agency's verdict was that the proposed drilling was exempted from EIA. Following the positive results from the drilling the operators decided to start the preparation to construct a power plant using geothermal energy from the Hellisheiði field for production of electricity and hot water for space heating. An Environmental Assessment plan was submitted to the Planning Agency in April 2002 (VGK 2002) and subsequently approved. Work on the EIA is ongoing according to the plan.

8.5 Krafla

Both the Krafla geothermal field and nearby field of Námafjall were developed for energy production and industry long before the current Act on Environmental Impact Assessment came into action. But new development has been planned in both areas and Environmental Impact Statements prepared.

Krafla.

The present drill field covers only a small part of the large Krafla caldera, but the geothermal area is located within the boundaries of the caldera. The original production permit was for 60 MW. Drilling in recent years has resulted in more steam production than is needed for the present plant and therefore the operators of the Krafla field, Landsvirkjun, plan to increase the plant to a 100 MW capacity using the present excess steam with steam from additional drilling. The operation involves an additional power house and cooling tower. An Environmental Impact Report (VGK, Orkustofnun 2001) was prepared and in December 2001 the Planning Agency approved the proposed activities. The Food and Environment Agency, which issues the final operation permit, has reservations about the chemical composition of the potential effluent from the larger plant and demands stringent conditions if it is to issue such a permit, but the Planning Agency approved the mitigation measured proposed by the operators of the plant. The operators of the Krafla power plant have also made a plan to investigate whether additional prospects suitable for development can be found within the Krafla caldera. Therefore four possible targets have been marked, and a declaration report (VGK, Orkustofnun 2000) delivered to the Planning Agency in accordance with Appendix 2 of the Environmental Act. The current drill field is centrally located within the large geothermal system in the Krafla caldera, but the four proposed new drill fields are bordering the current drill field on all sides. In the Agency’s decisions each of the four areas were dealt with separately, two of them being exempted from EIA (i.e. Eastern and Southern fields) but the other two not (Leirhnjúkur area and Western field). The main reason for requesting an EIA is the proximity of the exploration area to the Leirhnjúkur craters, the center location of the Krafla fires 1975 – 1984. On a nature protection map produced by the Nature Protection Agency (1987) land is divided into five groups according to protection value. The Leirhnjúkur area is in the second priority group, the highest in the Krafla area, due to its scientific and educational importance and because of its tourist attraction. The EIA is requested to evaluate possible irreversible damage to the environment, pollution and disturbance to tourism. It is pointed out that although Landsvirkjun has the rights to geothermal development in Krafla then the proposed drilling area is defined in the municipal development plan as a “wilderness area”. Any drilling activities would require an amendment of the general development plan and drilling would have to take place within an “industrial area”. There is also controversy about a specific law on the protection of Lake Mývatn and River Laxá (No. 36/1974), which was passed specifically for the protection of these phenomena but is for convenience valid for the whole district of Skútustaðahreppur to which the Krafla area belongs. Another problem is whether the environmental impact of potential utilization should be estimated concurrently with the assessment for an exploration well.

Following the Agency’s decision the operators decided to prepare an EIA for the Western field, and an action plan was submitted in February 2002, and an EI report in June 2002. The Planning Agency’s verdict was issued in September 2002. The finding was that the proposed drilling and construction activities would not cause an irreversible environmental impact, and the project was approved. An amendment of the general development plan for the field in question must be made prior to the issuing of the final operation permit.

Námafjall, Bjarnarflag

Steam from the Bjarnarflag field has been utilized for industrial use and for a small power plant (3 MW_e) for decades. Landsvirkjun, which has the geothermal rights in the whole of the Námafjall geothermal field, has made plans for a 40 MW_e geothermal power plant at Bjarnarflag. An Environmental Impact Statement (Hönnun 2000) was delivered to the Planning Agency. There the drilling of up to 7 new production wells is proposed, additional to two existing wells, which have been in production for almost 20 years. Despite an extensive assessment of the environmental impact of the proposed drilling and testing of boreholes and the construction and operation of power plant and power lines, the agency’s verdict was that further investigation and evaluation were required. The Agency’s conclusion was that the operator had not demonstrated that the need for the construction and economic benefits justified the unfavourable environmental influence, especially the visual pollution. Several subjects where more information is required are listed in the report, these include:

1. Compare different potential locations of the various buildings and accompanying steam emission, with emphasis on the visual influence as viewed from various popular tourist spots in the neighbourhood.
2. Compare different construction possibilities, such as surface versus sub-surface steam pipes, overhead power lines versus sub-surface cables, and different well locations.
3. Evaluate various options for disposal of wastewater from boreholes and power plant.
4. Evaluate possible changes in geothermal surface manifestations.
5. Evaluate the impact the planned activities will have on tourism.
6. The situation at the end of the 50 years operation period.

A proposal for a new EIA is now in preparation (Hönnun in preparation) and the reaction of the National Planning Agency is awaited.

8.6 Relevance to IDDP during pilot studies

When reviewing the verdicts from the Planning Agency, it is clear that the drilling itself is usually not the main environmental concern but rather items such as road construction and excavation of material. Geothermal areas are often important tourist attractions, and apparently there is a growing tendency not to open up new areas for geothermal development. An area where there is already good road connection is more likely to be accepted by the Planning Agency for development than a complete wilderness. If an IDDP borehole will be located within a borefield of an approved power plant, or it will involve deepening of an existing borehole in such a field, it is likely that road construction and other surface disturbances will not cause serious environmental concern.

The main “geothermal” related concern is the disposal of waste water from boreholes, either during testing or utilzation. When the IDDP project will be evalued, the disposal of waste fluids is likely to cause concern, as the purpose is to obtain fluid which we are not familiar with and might well contain various elements in higher concentration than is suitable to the environment, unless preventive action is taken.

An operator of an existing power plant is allowed to drill replacement wells within the approved borefield in order to maintain the output of the plant without approval from the Planning Agency. One of the objectives of the proposed IDDP project is to design and build a pilot plant to study the supercritical hydrous fluid. An IDDP borehole, although drilled within an existing borefield, cannot be classified as a replacement well, and therefore the IDDP falls under projects listed in Appendix 2 of the Environmental Act. Deepening of existing wells (wells of opportunity), however, is not expected to need an EIA. An overview of geothermal EIA in Iceland is shown in Table 9.

Table 9. *Environmental Assessment of Geothermal Projects in Iceland – Overview*

Location	Project	Report	Year	Comment
Reykjanes				
Reykjanes	Drilling and development	EIA	2002	Plan accepted
Trölladyngja 1)	Exploration drilling	App.2	2000	Plan accepted.
Hengill				
Nesjavellir 1)	Installed capacity 90 MW	EIA	2001	Plan accepted.
Hellisheiði	Exploration drilling	App.2	2001	Plan accepted.
Ölkelduháls	Exploration drilling	EIA	1994	Plan accepted
Grændalur	Exploration drilling	EIA	2001	Rejected
Krafla				
Leirbotnar, Suðurhlíðar 1), Hvíthólar	Installed capacity 100 MW	EIA	2001	Plan accepted.
West, Leirhnúkur, East, South	Exploration drilling	App.2	2001	Two plans accepted.
West	Exploration drilling	EIA	2002	Plan accepted
Námafjall (Bjarnarflag)	40 MW_e Power Plant	EIA	2000	Report requested

1) Deepening of existing wells (TR-01, NJ-12, KJ-18) unlikely to need assessment

9 SITING OF IDDP WELLS AND PRIORITY ORDER

Table 10. *Priority list of potential IDDP drillsites at Reykjanes* **:**

Drillsite	**Priority**	**Temperature**	**Permeability**	**Environ./geography/climate**
RN-12	**1**	High	High	Already 2500 m deep/no liner
Stampar	**2**	High	High	Adequate – and a stepout
RN-11	**3**	High	High	Already 2300 m deep with liner
Center elsewhere	**4**	High	High	Adequate

Table 11. *Priority list of potential IDDP drillsites at Nesjavellir and Hengill :*

Drillsite	**Priority**	**Temperature**	**Permeability**	**Environ./safety./climate**
Kýrdalur near NJ-12	**1**	Higher	Higher	Depending but safe
Kýrdalur near NJ –17	**2**	High	High	Depending but safe
Nesjavellir valley SE	**3**	Medium	High	Depending but safe
Nesjavellir valley NE	**4**	Lower	Medium	Depending but safe
Nesjavellir NJ-11	**0**	**Highest**	**Highest**	**Not safe yet** due to high P-T
Hengill centre	**?**	High	High	Undrilled field
Hengill south	**0**	Coldest	High	CP out of reach

Table 12. *Priority list of potential IDDP drillsites at Krafla :*

Drillsite	**Priority**	**Temperature**	**Permeability**	**Environ./geography/climate**
Hveragil	**1**	High	Highest	Depending on siting
Hlidardalur	**2**	High	High	Adequate
Margin elsewhere	**3**	Lower	Medium	Depending north/south
Center elsewhere	**4**	High	Lower	Depending summer/winter
KJ-18	**5**	Lower	Low	Depending summer/winter

A priority order for the selected IDDP drillsites at Reykjanes, Nesjavellir and Krafla is presented in Tables 10-12 above. The principal task of the geosciences group in siting an IDDP well, was discussed and evaluated to some extent at all the IDDP/ICDP workshops. The first aim of the Geoscience Panel at workshop No.1, for instance, was to help define the drilling target by specifying the likely range of conditions of fluid temperature, pressure and composition, and of lithology and permeability that might be encountered at depth in the three sites being investigated in the feasibility study. Depending on the initial salinity of the recharge water, minimum supercritical temperatures will be in the range 375 to 425°C, and minimum fluid pressures in the range 225 to 350 bars. Depending on the temperature gradient this will require drilling to 3.5 to 5 km depths.

The chemical composition of supercritical fluids in different localities in Iceland will be different, as some have originated as meteoric water and others as seawater. At different times in a given locality, supercritical fluids may temporarily contain volcanic gases evolved from magmas intruded along the rifts during volcanic episodes. A general consensus also ensued that scaling problems would be greater in a system involving seawater, as expected at Reykjanes, as compared to more dilute water systems as at Nesjavellir and Krafla. In particular, it is expected that sulfide deposition will be more extensive from seawater as compared to dilute water systems. Also acidity due to transfer of gases from the magma heat source is known to enhance rock dissolution and in this way intensify sulfide deposition during decompression and cooling.

As discussed in part III of the feasibility report, preliminary well simulator models carried out as part of the feasibility study indicate that temperatures of 450°C or greater, at initial fluid pressures of 350 bars or less, are necessary in order prevent the fluid from entering the two-phase field liquid water plus “wet” steam, during ascent and decompression. It is possible that the steam produced in the resulting 2-phase mixture might have an enthalpy no higher than steam produced from a “conventional” geothermal well that taps a liquid water reservoir. However, the mass fraction of that steam in the 2-phase mixture that results from adiabatic decompression of supercritical fluid should be much greater than that generally produced by flashing steam from a liquid water reservoir.

With all this and other factors in mind, recommendations from workshop 1 with respect to site selection for **the first deep** IDDP well were made as follows:

(1) Drill where the supercritical zone is likely to be at the lowest pressure and shallowest depth. Not only does this reduce the drilling costs but should also lead to higher enthalpy of the discharged fluid at the wellhead. It should also lead to lower concentrations of dissolved solids in the fluid, and possibly better permeability. However it could lead to higher HCl than would be the case for production at higher pressure.

(2) Select a geothermal system of low salinity to minimize problems of scaling, corrosion and acidity.

(3) Avoid lithologies with rocks of silicic and intermediate composition as they behave more plastically at lower temperatures than do basalts, and are likely either to have poorer permeability or to contain fluids and gases at, or near, lithostatic pressures. Still a note need be made on fracture permeability at the acid intrusive rock contacts at both Krafla and Nesjavellir, most of which involve many of the best feed points within the well fields

(4) Drill where indications in the shallower reservoir and geophysical studies suggest the existence of permeabilty at the depth of the supercritical zone.

(5) Play safe by siting the first deep well of the series where the available data are adequate to meet the above criteria so that the possibilty of failure is minimized.

All considered, both within each drill field as prioritized in Tables 10, 11 and 12, and between the three drill fields considered, the following priority order for the first IDDP drillsite is made :

I Nesjavellir
II Krafla
III Reykjanes

Without extending this discussion much further, the selection for the first IDDP well, also depends on other factors, which will affect Deep Vision’s decision on the first drill sites. The first priority drillsite within a field as recommended above, may possibly interfere with current plans on power production, or environmental considerations, and so forth. Lack of funding, for instance, might lead to the selection of a very worthwhile pilot hole project in a well of opportunity. Well KJ-18 in Krafla may serve as an example, a drillsite rated relatively low in comparison to better sites further west. Still it would meet the request of a supercritical temperature within reach, while permeability might be low. An advantage, i.e. the lower probability of encountering volcanic gas compared to the high permeability zones further west, can be mentioned. Well KJ-18 is not being used by the energy company, except for monitoring, and an IDDP activity there is not likely to interfere with other activity within the drill field. Possibly, the deepening of well KJ-18, might result in a production well, beneficial to the energy company, and so forth. Similar arguments apply to the other drill fields.

Still, to meet the principal goal of IDDP of studying the economics of exploitation of a supercritical fluid zone beneath a conventional high temperature system, and to play safe along recommendation (5) above, Nesjavellir (priority 1) becomes the first reccomended site, and Krafla (priority 1) the second selected one. A positive result on the first IDDP well, would result in a series of deep wells in the near future.

In the event of an IDDP well not meeting the expectation of becoming a potential high energy producer, the experiment could be reversed in an attempt to enhance the overlying geothermal reservoir. Injection of water with chemical tracers could prove useful. In preparation for drilling the IDDP well such an injection test can be considered after each coring phase.

10 FUTURE PLAN AND SCIENCE ACTIVITIES

Based on the IDDP feasibility study, the Icelandic energy companies will need to reach a conclusion on **if and when** to continue the IDDP project. If the decision will be to continue IDDP, and the decision is not delayed for too long, the next logical step is to seek domestic and international partners and funding for the drilling and science activities. However, prior to this, a very important decision on where to drill the first IDDP well needs to be made. That decision depends entirely on the energy company holding the drillfield in concern. For example, if one of the energy companies, decides not to allow access to its drill field, or a given part of it, for the first IDDP well, that field (or the part of it) will be excluded from the list of IDDP drillsite options as soon as possible. That will simplify the selection of drillsite and the type of well to be drilled. The company concerned, might still intend to participate in IDDP, and the reason for not allowing access to a drill field or a well of opportunity for the time being, might relate to interference with current industrial plans, environmental restrictions etc. **The sooner the energy companies select the wellsite options available, the better**.

Assuming that the energy companies decide to proceed with IDDP, the next step will be to decide **where to drill and what type of well**. That decision depends on available funding and potential partners. For example, some partner might demand a drillhole sunk into a saline field as a prerequisite for participation. Others might request some tests, like tracer or injection tests during drilling be performed. **The sooner the options for the type of drillholes are clarified the better.** For example, if the potential partners decide to begin to seek funding for a pilot hole in a well of opportunity, the rest of the planning process focusses on that option.

Once the potential IDDP target has been selected, there is a need for extensive preparation and planning activity for drilling, funding being most important. Applications for funding from international funding agencies or the industry take time. Two years do not seem unrealistic. The **preparation of a firm cost estimate** for the drilling and science operations to be performed at the site selected, and the **making of a detailed science plan** and **organizing the research activity** to be executed, **prior- , during- and after drilling,** is of prime importance.

The establishment of the SAGA group, and the IDDP/ICDP workshops I and II, particularly focussed on addressing a reliable drilling plan to reach the IDDP goals, and to begin implementing a science plan and organizing the research activities. The international team of experts, participating in the workshops, considered it pretty important to initiate this process during the feasibility stage of IDDP, and evidently influenced the study to the mutual benefit of both. This collaboration has been particularly fruitful to us, and is reflected in all three parts of the IDDP feasibility report. Part one of this report, on geosciences and site selection, is concluded by recommendations made by the international forum at the IDDP/ICDP workshop 2, straight from the SAGA report No.3, and addressing the science plan and reasearch activity:

10.1 Report of the panel on rock studies

The purposes of the proposed petrological and geochemical studies are to :

(1) determine the protoliths and the volcanological, hydrothermal and tectonic history of the site(s) chosen for deep drilling. This is relevant to elucidating the formation of

ophiolite sequences and ocean crust, and the volcanic processes, magma evolution and fluid movement at spreading centers.

(2) determine mineral parageneses and calculate mineral-fluid equilibria in the subcritical to supercritical regions. The geochemical, mineralogic, and geophysical data will be used to evaluate solution-mineral equilibria under both subcritical and supercritical conditions. Mineralogic phase relations and parageneses will be combined with thermodynamic properties of mineral components and fluids, to compute chemical affinities of pH and redox sensitive reactions. This will provide a basis for developing reactive mass transfer models.

(3) evaluate mass transfer. The effects of protolith (compositional as well as petrophysical) properties, of temperature, of metamorphic grade, and of fluid composition on mass transfer will be evaluated. Quantifying volume changes due to water/rock reaction can be addressed by assuming conservation of mass for one or more immobile components. Another approach is to quantify trace element mobility during basalt alteration. Comparative analyses of trace element concentrations of geothermal fluids and secondary minerals from the production zones in specific drillholes will allow evaluation of the degree to which trace element concentrations of aqueous solutions are controlled by partitioning equilibria with secondary minerals.

(4) model the magma-hydrothermal system including the supercritical regime. Investigation of the dynamics of hydrothermal activity and near-critical behavior will involve establishing the thermal stages of the system from analysis of thermal gradients, micro-seismic and conductivity datasets, distribution functions of fluid inclusions, and curvature of thermal fields. The chronology of fluid percolation paths and the nature of alteration mineral assemblages and mineral zonation patterns will help detect near-critical behavior, and provide input for computation of models of magma-hydrothermal interaction.

Sample Requirements. In view of the very small amount of drill core available from the geothermal systems being considered as targets by the IDDP, it is desirable to obtain as much core as possible. The highest priority is for cores below 2000 meters depth, in or near the supercritical zone, and specifically near zones from which fluid samples are obtained. If the IDDP drills a core hole by re-entering and deepening an existing well it would be desirable to consider collecting side-wall cores in the open interval in that well, or else coring a slim hole alongside it, if costs and technical considerations permit. Similarly preexisting rock samples and data already available from a borehole that is to be deepened should be retained and curated by the IDDP for study by the project.

Studies During Drilling. Because of the need to recognize supercritical zones in real time, and to anticipate potential hazards during drilling, it will be necessary to operate a petrographic laboratory at the well site equipped with at least fluid inclusion and thin section capabilities. Otherwise sample handling and curation will be patterned on past ICDP projects (for example the Hawaiian Scientific Drilling Project). A formal sample-handling protocol will be implemented. The basic core description should include lithology, alteration, stratigraphy, structural and extrusive/intrusive relations, and pre-drilling fracture distribution, orientation and cross-cutting relations.

Post-drilling Studies. Subsequent petrographic descriptions should start with detailed descriptions of primary mineralogy and textures and secondary or alteration mineralogy and textures. These studies should address alteration and replacement of primary minerals and deposition of secondary minerals in open spaces and within vesicle- or vein-wallrock zones adjacent to healed fractures. Geochemical studies of whole rocks, minor and trace elements and stable and radioactive isotopes will then follow, according to the needs of specific investigators. Samples will be selected for geochronologic and petrophysical characterization including porosity and permeability, electrical resistivity, seismic velocity, natural gamma/neutron density, and magnetic susceptibility and paleomagnetism.

Integration and Interpretation. Most importantly these data will be integrated with regional geologic and geophysical data, paying specific attention to the nature and history of the fracture network and to the relationship of this network to the tectonic and geothermal history of the system on local, regional and global scales. All of these proposed studies are relevant to furthering our understanding of the origin, nature and economic potential of the supercritical zones in Iceland. In terms of global geoscience these studies also relate to issues such as: the time and spatial relationships in fluid chemistry, alteration minerals, and isotopic systematics during evolution of sub- to super-critical geothermal systems on an ocean-spreading ridge; the mantle contribution to volatiles in ocean-spreading ridge hydrothermal systems; and global geochemical cycles that control, for example, ocean chemistry. Another example would be mechanisms for the generation of methane and higher hydrocarbon compounds in water-basalt geothermal systems, with implications to the global methane flux.

10.2 Report of the panel on fluid studies

The fluid studies panel outlined a program of study that addresses fluid sampling, analysis, and interpretation, and it identified tasks that must be completed before and during drilling. The panel discussed the relative merits of the three areas being considered for drilling and concluded that drilling into supercritical conditions could give valuable results in all of them. However, drilling at Reykjanes would be of more interest to the international scientific community primarily because of the interest in black smokers, ophiolites, and mid-ocean ridge processes.

One of the principal emphases of the fluid sampling program should be to obtain matched fluid and rock samples at fluid production points in the deep reservoir, since the chemistry and thermodynamics of the geothermal system can only be adequately described and interpreted from a knowledge of the total rock-water system. Such paired fluid-rock samples would be among the most valuable scientific products of the drilling. Such samples will optimize the ability to interpret both fluids and minerals, and would open opportunities for novel thermodynamic studies.

Depending on costs, a second desirable goal would be to core the entire length of the drill hole. Among reasons for such coring is the embarrassing lack of information from cores in Icelandic geothermal systems in general, and ability to address specific questions such as why δD in deep fluids at Reykjanes is ca. -20 $^{0}/_{00}$ even though these fluids are apparently modified seawater.

Ideally every fluid-producing horizon should be sampled during drilling, and, ideally, each productive horizon should be cased off or cemented so as to prevent mixing of fluids from distinct aquifers. This would entail suspending drilling for a period to allow thermal recovery and to flush out drilling fluids by the production of fluids from the well. If drilling were to be stopped immediately when total loss of circulation occurs, a roughly representative sample of the fluid could likely be obtained after two or more days of discharge. Unfortunately, such an extensive program of sampling would be time-consuming, expensive, and technically difficult. However the scientific value of the fluid samples is great. A further concern is that repeated thermal cycling would be detrimental to the integrity of the well casing due to thermal stresses and possible damage by corrosion or scaling. Some participants argued that this plan for sampling is contrary to the concept of the “pipe”, that was discussed extensively at Workshop No. 1. This “pipe” is a replaceable liner intended to protect the well casing against corrosion and scaling.

Owing to various problems with discharge samples (e.g. loss of material to scale, indefinite fluid-gas ratio), it would be most beneficial to obtain downhole fluid samples in addition to well head samples. Downhole samples still require well flushing to clear drilling fluids and to recover the aquifer temperature and pressure, so there is no benefit in that respect. Downhole samples can be obtained by mechanical, electronically controlled devices, or by a novel approach using artificial fluid inclusions. High temperature downhole samplers are under development in New Mexico and Canada that might be deployed for this project. Techniques for artificial fluid inclusion sampling, including potential millimeter-scale inclusions, still need to be developed experimentally, partly involving methods under development at Tohoku University.

Preferably, fluids would be analyzed for nearly all elements of the Periodic Table as well as for key anionic species and light stable isotopes (H, B, C, O, N, S etc.). Sampling and analysis of both filtered and unfiltered samples is necessary. Quantification of many trace elements is considered a valuable contribution of the project that sets it apart from previous studies. Large, ultrafiltered samples for the determination of organic constituents may well be of interest to many scientists. The cost of complete fluid analyses would be small compared to the cost of obtaining the samples.

Recovery of hypersaline brines produced by supercritical phase separation would be of great interest internationally. A careful consideration is required of the nature and the likely residence, of such brines in supercritical systems.

Modeling of fluid properties before drilling will be useful. Such modeling should include boiling of fluids to identify potential mineral scale deposition and fluid pH, thereby aiding in site selection and well design. Such modeling will be tested when the “pipe” is later removed to identify scale minerals formed at each set of discharge conditions. A combination of modeling and experimental work based on produced fluids and rock samples would lead to the derivation of the thermodynamic properties of solid solution end members such as manganese and nickel chlorites, which are not available at present. A study of chemical species involved in slow redox reactions, such at the CH_4-CO_2 and the SO_4-H_2S equilibria, would be of great interest. Such a study would probably require rapid analysis of fluids at the wellhead.

<u>Interpretation of fluids and minerals.</u> The interpretation of the fluid chemistry will rely on fluid analyses, results of measurements of physical parameters, and on minerals identified in rock samples matched to fluids. Concentrations of incompatible components in altered rock, fresh rock and fluid are essential to constrain the origin of the fluid and to gain a quantitative understanding of water-rock reactions and water-rock ratio. Isotopic data on minerals and fluids in combination with theoretical modeling of mineral saturation in reconstructed fluids with comparisons to the actual observed minerals will enable the development of a well constrained model of the fluid and mineral origins.

Summary. Ideally, we would like to sample fluids from every significant fluid inflow point in the well during drilling, then case off or cement those inflows so as not to mix fluids from separate aquifers. In each aquifer, we would like cored rock samples to match to the fluids. In practice, this ambitious sampling program would most likely have to be scaled down, and focused on the zones of greatest interest. All fluids should be analyzed for a very large set of major and trace elements, light stable isotopes and key molecular species. Using such analyses in conjunction with matching whole rock analyses and analyses of individual minerals, and with numerical modeling methods, we expect to be able to reconstruct the physical and chemical evolution of the supercritical geothermal system.

10.3 Report of the panel on reservoir studies

From the point of view of reservoir studies the well itself has the highest scientific value. The well itself will confirm or reject the existence of an economic resource at depth. Temperatures higher than the critical temperature have been measured in wells in Italy, the United States and Japan, confirming the presence of potential high-enthalpy resources at those locations. However, the well Nesjavellir No.11 seems to be one of the few examples world-wide where a mass flow has been observed at such high temperatures. Two other examples are the San Pompeo No. 2 well in Larderello, Italy, and the Wilson No.1 well near The Geysers, California.

There will be substantial difficulties in obtaining representative values for reservoir properties from the IDDP well. Coring or any type of drilling will most likely cause some fracturing of the rocks and the parameters measured on the core in the laboratory will most likely reflect only approximate *in situ* values. The same situation can also be true for the fluid that may be contaminated or changed by phase separations before sampling.

There are several problems in state of the art reservoir simulation. At present most simulations of fluid behavior in reservoirs assume properties of pure water, while in reality saline solutions or, alternatively, dilute solutions containing high concentrations of dissolved gas are likely to be present. Temperatures and pressures of critical points of these natural fluids, and their densities and viscosities at and near their respective critical points may be significantly different compared to pure water. Also, even in the case of pure water, physical properties exhibit singularities near the critical point, and these circumstances cause difficulties in conventional simulation work. Simulation with relatively coarse grid has been carried out with reasonable results, but simulations with a fine grid close to the critical point become unstable. Present computer codes are not well suited to describe the behavior close to the critical point and better knowledge about the physical properties of the fluid are needed. Some laboratory experiments could improve the situation. On the other hand, the porosity structure of the rocks (porous versus fractured media) would not have much influence on simulation work in the supercritical region as mobility of a very dilute fluid, or the gas phase boiled off from a highly saline brine, is expected to be very high in the supercritical region.

Recommended Pre-drilling Activities. a) Numerical simulation. Carry out a parameter study describing how a supercritical system could be feeding a conventional sub-critical geothermal system. b) Laboratory experiments on the physical properties of the fluid. c) Detailed mapping of earthquake hypocenters in the drilling areas in order to map the minimum depth of the brittle crust. d) Magneto-telluric measurements to locate the top of the critical zone.

Recommended Activities during Drilling. a) A pressure temperature (P/T) memory tool should be attached to the core barrel at all times. During core recovery, a new tool would be attached. The pressure and temperature would be recorded immediately after the return to surface giving a fairly continuous record of the P/T conditions in the well during the core operation. (No extra rig time. Highest priority). b) Another P/T memory tool should be attached to the outside of the drill pipe. This tool would be retrieved when the drill bit is changed. The purpose of this P/T registration is to achieve pressure- and temperature gradients in the well during drilling. (No extra rig time. Medium priority). c) When significant loss of circulation is observed, an injection test should be carried out in order to record the transmissivity of the well. (The rig time required is 6-12 hours. Highest priority.) d) Downhole logging should be carried out every time the bit is changed. Each log should cover the depth interval from the last change of the bit. (Rig time required 6-12 hours.

Medium priority.) e) A microseismic and an SP array should be arranged at the drill-site providing a continuous record of these parameters. Recording would start some months or a year before the drilling operation starts and continue for at least one year after the drilling has been completed. (No extra rig time. Medium to high priority.) f) Continuous recording of gases in the flow line. The equipment would record both the concentration and the type of gases accompanying the circulation fluid. (No extra rig time. Highest priority) g) Upgrade numerical simulation during drilling, if required. (No extra rig time. Lowest priority.) h) A detailed mud logging will be carried out. The usual Icelandic procedure can serve as an example. (No extra rig time. Highest priority.) i) A complete logging program, including lithological logs will be carried out for the whole open hole section at the end of drilling. (Rig time required 24-36 hours. Medium priority.) j) Stimulation of the well by massive cooling of the open hole section and/or by placing a packer into the well and pumping water under pressure into the zone below the packer. (About two days of rig time required. Highest priority.) k) Repeat the wire line logging in order to detect any changing in the condition of the formation due to cooling of the well. (Rig time required 24-36 hours. Highest priority.) l) Vertical seismic profiling and walk away seismic profiling should be carried out in the cold well. (Rig time required 24-36 hours.)

Recommended Post drilling activities. a) Temperature and pressure logging during the thermal recovery of the well. The recovery time might be of the order of weeks or even months. Higher frequency of logging is required at the beginning of this time than in the end. These logs give the most reliable information about the location and the nature of the feed zones in the well. (Highest priority.) b) Recording in the seismic and the SP array should continue for about one year after the drilling has been completed. (Medium priority.) c) Down-hole fluid sampling can be done in connection to other logging activities performed at this time. (Lowest priority). d) The panel recommends strongly that “the pipe” (the pilot plant) will be constructed in such way that it can be heated by an external source (induction heating?) and provided with sensors to monitor the temperature of “the pipe”. By keeping the pipe at a constant temperature above the critical point (say at 400°C), the formation of acid by hydrolysis reactions can be avoided. At the same time, keeping the pressure gradient from the bottom to the top of the pipe as small as possible will minimize the risk of scaling in the pipe.

10.4 Report of the panel on technical issues

This panel was concerned with drilling, well completion and sampling. It benefited from the extensive background provided during IDDP Workshop No.1. Importantly, it concluded that no apparent insuperable technical problems with completing either a pilot hole or a deep hole drilled from the surface to satisfy the scientific objectives of the IDDP.

The panel discussion on drilling cost during the workshop was based on preliminary data and updated cost estimates will be dealt with in part II of the feasibility report.

An overriding concern is the safety of any drilling into or near supercritical conditions. This concern was expressed in a discussion of the casing program as well as cycling the well during flow tests and attempts to acquire fluid samples. A number of options for sampling fluids from the well without flowing were discussed. These options included down-hole sampling devices as well as the growth of artificial fluid inclusions. At the Kakkonda hole in Japan (> 500 ^{o} C), a form of reverse circulation drilling was used to acquire a fluid sample.

Information on new technologies that could be of value for this project was presented. This included concepts of drilling with casing and of expandable casing. Expandable casing can be used to case a well without size reduction. This is accomplished by inserting casing through an existing string and then expanding the casing once it is in place. Similarly, the Sandia National Laboratory of the USA is working on the development of high-temperature tools for the geothermal industry. Some of these prototype tools could probably be made available for use in an IDDP well.

The high projected cost of the IDDP wells is of obvious concern. Additional recommendations from the scientific panels that a well be cored from the surface to TD would increase the drilling cost estimated. An alternative option is to enter an existing well and drill or core to a greater depth. This option could be considered as a "pilot hole" or "well of opportunity" since it would be testing coring and sampling technology in the pressure-temperature zones defined as being of highest scientific interest. The option has a cost advantage since much of the large diameter drilling and casing would already have been installed. The panel listed the wells that would potentially fulfill the role of a "well of opportunity" .

The general condition of these wells and the willingness of energy companies to make such a well available to the IDDP needs to be addressed. According to the data listed in Table, the most likely candidate wells would be No. 18 at Krafla and NJ-12 at Nesjavellir. The relative merits of these options involved the present condition of the wells, their scientific advantages, and the need for permission by the owners for IDDP to gain access to the wells. Orkustofnun, the National Energy Authority of Iceland, was given the assignment of reviewing the files and making a recommendation to SAGA and to the Principal Investigators.

10.5 Evaluation of the wells of opportunities

After workshop II , the Orkustofnun team working on the feasibility report in addition to those attending the workshop, reviewed quickly the primary drillhole data on the so called "wells of opportunities" discussed at the workshop. Immediately, some of the listed wells could be eliminated from the list for a variety of reasons. Some were permanently damaged, others had experienced technical problems, and some were unavailable production- or reinjection wells at present. Soon the discussion focussed on 5 options, i.e. two wells at Nesjavellir (deepening of NJ-12, and a new inclined well near NJ-12 drillsite), one at Krafla (well KJ-18), one at Reykjanes (RN-11) and one at Trölladyngja (TR-01) on the Reykjanes peninsula (see Figures 3 and 4). Since this evaluation, a new 2500 m deep well, RN-12, has been drilled at Reykjanes, closer to well RN-11 (2248 m deep). Both the RN-wells are 12 ¼" wide production wells, and both are without a slotted liner. If available as well of opportunities, RN-12 is of higher preference.

No definite conclusion was reached on the wells of opportunity by the Orkustofnun team. The wells vary in three fundamental properties. The Krafla KJ-18 well, and the Nesjavellir NJ-12 well, were both drilled with an 8 ½" drillbit, whereas the RN-wells and the TR-01 well are drilled by a 12 ¼" bit to the bottom. Only KJ-18, RN-11 and RN-12 are without a liner, the others have liners, which may or may not be retrievable?

The two wells at Reykjanes, accordingly, do have the IDDP well profile of a type-B well, and as such can be classified as IDDP-wells proper. Core drilling in either well, in one or two steps, from 2,5 to 4 or 5 km, is readily attainable, once a 10 3/4" casing has been inserted and cemented. Subsequently, "the pipe" for fluid handling and evaluation (FHE) can be inserted and tested, and this well of opportunity would not be different from a proper IDDP well.

Well KJ-18, on the other hand, is only 8 ½" wide down to 2200 m depth. A 5" to 7" casing could be inserted and cemented, followed by single step coring , say down to 4 km.

The FHE-pipe cannot be inserted, and the well would need to be flow tested by a conventional method. Accordingly, deepening of well KJ-18, would need to be classified as a "pilot project" preparatory to IDDP, as discussed in SAGA report No.3.

The same applies to well NJ-12 at Nesjavellir, if the hanging liner is retrievable. Due to the liner, and the high pressures expected at relatively shallow depths, when the main upflow zone targeted across the eruptive fissure is entered, the option of drilling a new well adjacent to NJ-12 was also considered. The benefit of a new well, be it inclined or straight, is first and foremost a safety concern, in view of the proximity to well NJ-11 and the high P-T condition encountered at shallow depths in 1985. The cost benefit of this type of a well of opportunity is small, and evidently it is just a matter of taste whether a new well at NJ-12 should be classified as a "well of opportunity" or a proper IDDP well. A new inclined well near NJ-12, targeted to encounter a supercritical fluid at 3-4 km depth, would be the shallowest target available in Iceland, and no different from a high priority IDDP wellsite discussed in earlier chapters.

Once Deep Vision decides on what type of IDDP well to drill and where to drill it, a detailed evaluation of the wellfield in which the target-well is situated should be undertaken, and a detailed cost estimate made.

10.6 Scientific proposals

Some 40-50 scientific proposals and letters of interest for participation in IDDP and suggestions on geoscientific projects to be carried out prior to, during- and after the IDDP drilling, were made at the IDDP/ICDP workshops and meetings. Subsequently, additional proposals and letters of interest for science studies, have be submitted to IDDP. Access to most of these is made available on a CD accompanying this feasiblity report. These are abstracts from the IDDP/ICDP workshop proceedings and power point presentations, and should be considered as an inseparable part of this feasibility report.

Once Deep Vision has reached a decision on continuing IDDP, the organization and the implementation of a science plan becomes timely, and all the science proponents will be notified in order to reinstate their expression of interest on participation in IDDP. The notice will be sent as early as possible in order to meet with the proponents' needs to organize and seek funding for participation well in advance.

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IDDP

Feasibility Report

APPENDICES :

To Part I :

SAGA Report No. 1
SAGA Report No. 2
SAGA Report No. 3

IDDP SAGA Report No.1, June 2001
Compiled by the PI's, with input from SAGA members, DeepVision and S.Thorhallsson , 19.07.2001

REPORT OF THE ICDP-PI-SAGA MEETING ON THE ICELAND DEEP DRILLING PROJECT, REYKJAVIK, JUNE 22-27, 2001

INTRODUCTION

The Iceland Deep Drilling Project (IDDP) plans to drill one or more boreholes deep enough to penetrate into the supercritical zones believed to be present beneath three currently exploited geothermal systems in oceanic ridge-type spreading centres in Iceland. The main aim is to produce much higher enthalpy fluids for power production than are currently being utilized. The IDDP is being funded by Deep Vision, a consortium of Icelandic energy companies. A feasibility study, which has a budget of approximately US $ 300,000 is currently under-way and is examining the three candidate sites as well as the economics and engineering issues of drilling to greater depths and higher temperatures.

Responding to the invitation of Deep Vision, a meeting funded by the International Scientific Continental Drilling Program (ICDP), was held in Reykjavik, June 25th-June 27th 2001, to help defining tasks for the feasibility study and to begin planning a scientific program to take advantage of the IDDP borehole (see list of participants, Appendix 1). A ***Science Applications Group of Advisors*** (**SAGA**) with both Icelandic and international membership (see Appendix 2) has been formed to formulate and oversee these plans.

Iceland is a particularly favourable location for research on very high enthalpy fluids. It is hoped that such fluids can be produced at high flow rates. In Iceland the repeated seismicity and volcanic activity in the rift environments create high permeability and high temperatures at drillable depths. Temperatures greater than 300°C are commonly encountered in wells drilled to depths of 2 km in high-temperature geothermal fields in Iceland. The likely existence of permeable regions in brittle basaltic rock at supercritical temperatures at still greater depths beneath the candidate geothermal fields is inferred from the distribution of hypocentral depths of seismic activity that continues to below about 5 km depth. These circumstances are the product of the special geological environment of Iceland, a coincidence of a mantle plume with the divergent plate boundary at the mid-Atlantic Ridge. Thus the IDDP offers the international geoscience community a unique opportunity to:

(a) investigate the magmatic and fluid circulation character of the Mid-Atlantic Ridge (on land), and
(b) study and sample fluids at supercritical conditions.

These aspects of high-temperature hydrothermal systems have rarely been available for direct observation. **SAGA** convened panels on ***drilling techniques***, on ***geosciences***, and on the ***pilot plant.*** (see Appendix 3)

DRILLING PANEL. The assignment of the drilling panel was to evaluate a drilling strategy to meet the engineering goals, and to consider the additional steps and the costs involved of also meeting the science goals. After a description of the workplan and division of responsibilities by S. Thorhallsson, the panel on drilling technique, with advice from other panels on the likely ranges of depth, temperature, fluid pressure and fluid composition in the supercritical regime, considered a wide range of options for achieving the engineering and scientific requirements of the IDDP. These options included drilling:

(A) a "standard", albeit deeper, production well drilled with conventional geothermal technology with limited spot coring at casing points, near major stratigraphic boundaries, and within reservoir rocks
(B) a "standard" production well as in (A), above, with wireline sidewall coring to interpolate between conventional cores
(C) a cored pilot slim hole, followed by reaming out the hole to a production-diameter well using "hybrid" rotary-coring technology
(D) two wells, one a cored slim hole for science and the other a "standard" production well for engineering,
(E) a "standard" production well to 3.5 km depth and then continuously core a slim hole 1-1.5 km deeper using hybrid rotary-coring technology.

A schematic overview of the 5 options above is presented in Figure 1.

During discussion by the SAGA committee, a strong consensus emerged that option E offers the best compromise to meet both the engineering and science goals within realistic budget constraints. The largest drilling rig currently in Iceland ("Jötunn") has the capacity to drill and case a production hole as deep as 3.6 km. A continuous coring system with top-drive, such as the DOSECC coring rig, used successfully in a number of scientific drilling projects in the USA, could then be adapted to Jötunn, or to a similar rig, to deepen and core a slim hole into the supercritical zone. If flow testing this slim hole proved successful, sufficient information for proof of the concept of producing energy from supercritical conditions would be obtained. At the same time the science program would obtain abundant data and samples from the supercritical regime and rock samples from the deeper part of the Icelandic late Quaternary - Holocene Rift zone.

GEOSCIENCE PANEL. The assignments of the geoscience panel were firstly to develop criteria for evaluation of three candidate sites which have been proposed for the IDDP, and secondly to develop a basic science program essential to the scientific success of the project. The three geothermal systems of Reykjanes, Krafla and Nesjavellir were considered as candidate sites from both geoscientific and environmental perspectives. Given what we know at present of these systems, supercritical conditions are almost certainly likely to be found at drillable depth at all three sites. The current production zone at the Nesjavellir geothermal field, at the north side of the Hengill Central Volcano, was provisionally ruled out for environmental reasons. However, two 2 km-deep exploratory wells will be drilled in the south side of the Hengill volcano this summer. Depending on the findings from these wells, the Hengill area remains a candidate site for the IDDP.

Table 1, under the heading Drilling Target, summarizes findings of the Geoscience Panel with respect to the criteria for evaluation of the candidate sites. In the upper part of the Table are the best estimates of the anticipated conditions likely to be encountered at depths at the three candidate sites. At Hengill and Krafla, target temperatures of 500°C are sought which should be well into the supercritical zone at 5 km depth and 4 km depth respectively. At the Reykjanes geothermal system the produced fluid is evolved sea-water so that it is deemed advisable to avoid fluids at temperatures high enough to result in deposition of salt in the well during production. This requires target temperatures below 420°C.

Potential problems are listed below the statements about the drilling target at each site. Environmental restrictions are probably more likely at Krafla than at Reykjanes, but more information about possible environmental restrictions at Hengill is necessary.

The panel recommends that the focus of a basic, essential, minimum science program should be on the deeper hotter supercritical part of the borehole, but not to the total exclusion of the upper cased production well. A minimum program in the production well should include collection of drill cuttings for petrological study, and at each casing point, logging, obtaining spot cores, and determining the state of stress by hydrofracturing and the use of borehole televiewer.

In the continuously cored part of the well, below the production casing, real-time study of fluid inclusions and mineral assemblages while drilling could be used to help identify the proximity of the supercritical zone. Taking advantage of any massive loss zones, slim hole logging of this deep zone should be attempted. Similarly extensive fluid sampling and flow testing of loss zones in the supercritical regimes should be an important goal of the program for both engineering and scientific reasons.

A number of activities during the feasibility study were also discussed. These included mapping earthquake hypocentres and determining focal mechanisms in the candidate sites and setting up a working group of geochemists to estimate likely chemical parameters of the fluid to help design the fluid handling system, as well as for environmental contingency planning.

PILOT PLANT PANEL. Until more is known about the nature and volume of fluids likely to be produced from this borehole, the main objective of the pilot plant must be to obtain as much data and information as possible on the fluid and its properties. On the basis of this information further plans for utilizing the fluid will be laid out. Thus the panel suggests a pilot plant in steps where the first step is designed to be as simple and flexible as possible. At Reykjanes the target is a brine at 380-420°C containing 3-5 % by weight salt with an enthalpy of 2000 kJ/kg or higher. Because the critical point is elevated to higher temperatures and pressures by increased salinity, a supercritical zone may not be present at this tempererature. At Hengill and Krafla the target is 450-500°C fluid with an enthalpy of 3000 kJ/kg, possibly containing 0.1-0.2 % by salt. However, there is a high uncertainty about the P, T and chemical composition, and the likelihood of encountering acid fluids which would present technical and environmental hazards. The panel finds it of highest priority to carry out a chemical study of the expected conditions of the supercritical fluid. The study should also address the possibility of discharging such fluid to the surface without the risk of rapid plugging of the well.

The preliminary design centres on a downhole tubing system consisting of a suspended solid liner to convey the fluid to the surface to allow fluid sampling at the surface and studies of corrosion and scaling downhole. In this preliminary design only low mass flows are planned. In this way the properties of the fluid can be investigated and the danger of scaling assessed without risking plugging the well. When the properties of the fluid have been established, more extensive surface installations will be required to further explore the possibilities of utilization and process design, for both energy and chemical production. Also at this stage the production part of the well could be readied for more extensive flow testing for scientific, chemical engineering, and reservoir engineering purposes.

GENERAL CONSIDERATIONS

Funding. Assuming that the feasibility study is favourable, for example that it appears that supercritical fluid can be produced, and that the chemical study shows that it is likely the supercritical fluid can be discharged to the surface without a high risk of plugging the well in a short time, the SAGA committee endorses the principle that the Deep Vision Group should fund activities that are primarily for the engineering requirements of a production well. On the other hand, the science program should seek funding for the incremental costs of engineering and drilling which is primarily for the science program. Negotiations on cost sharing where activities achieve both engineering and science purposes might be envisaged.

Source of Science Funding. The funding of the basic science activities can be divided into two parts, firstly the incremental costs of drilling the well due to science activities, and secondly the cost of the science itself. The SAGA committee will seek to fund incremental engineering costs, and the basic science program, including curation and distribution of samples and data, by submitting proposals to international and national funding agencies. The committee will also solicit proposals from international investigators to develop a well rounded and focused science program beyond the basic on-site activities mentioned above. The committee will also welcome for review various add-on scientific projects that might be proposed.

A wide ranging discussion of possible funding sources included the International Continental Scientific Drilling Program, the Integrated Ocean Drilling Program, the European Union, the European Science Foundation, and the Ridge program of the US National Science Foundation, among others.

A science workshop on the IDDP is planned to be held in Reykjavik on March 15th-22nd 2002 with 50-75 participants. A meeting of SAGA will be held immediately after the workshop. A supplement to the ICDP funding would be desirable for this workshop. By the end of July this year, a notice requesting expressions of interest and one page science preproposals will be issued, with the deadline of November 1st. SAGA will review preproposals and issue invitations for the workshop early in January 2002. Consideration of submitting a second request for funding to the ICDP in January 2002 is still an open issue.

If drilling is to begin early in 2004, major proposals seeking funds for the science program and associated engineering should be submitted in late 2002 and early 2003 (see table 2). Finally, the members of SAGA are encouraged to publicize internationally the scientific opportunities of participating in the Iceland Deep Drilling Project (IDDP).

TABLE 1

GEOSCIENCE PANEL :
Suggested criteria for evaluation of the three candidate drillsites

DRILLING TARGET	**Reykjanes**	State of knowledge	**Hengill***	State of knowledge	**Krafla**	State of knowledge
Desirable **T** of Production **(°C)**	380-420	fair	~ 500	fair	~ 500	adequate
Desirable **P** of Fluid **(225-300 bar**)	likely	fair	likely	fair	likely	adequate
Minimum Target Depth (in **km**)	5	fair	5	fair	4	adequate
Min. Production Casing (in **km**)	4	fair	4	fair	3,5	adequate
Adequate Permeability Present	likely	fair	likely	fair	likely	fair
Expected Salinity	oceanic	adequate	dilute	fair	dilute	adequate ?
Additional Data Needed	yes		yes		yes	
POTENTIAL PROBLEMS						
Weather conditions during drilling	good	ok	good/bad	ok	good/bad	ok
Environmental issues favorable	probably	needed	?	needed	sensitive	needed
Availability of cold water for drilling	yes	good	yes	good	yes	good
Injection well necessary	yes	probably	yes	probably	yes	probably
Land Ownership	simple		simple		simple	

* Two exploratory wells, 2 km deep, will be drilled at Hengill summer 2001
* Nesjavellir is being ruled out for the time being for environmental reasons

PILOT PLANT PANEL : Evaluation summary

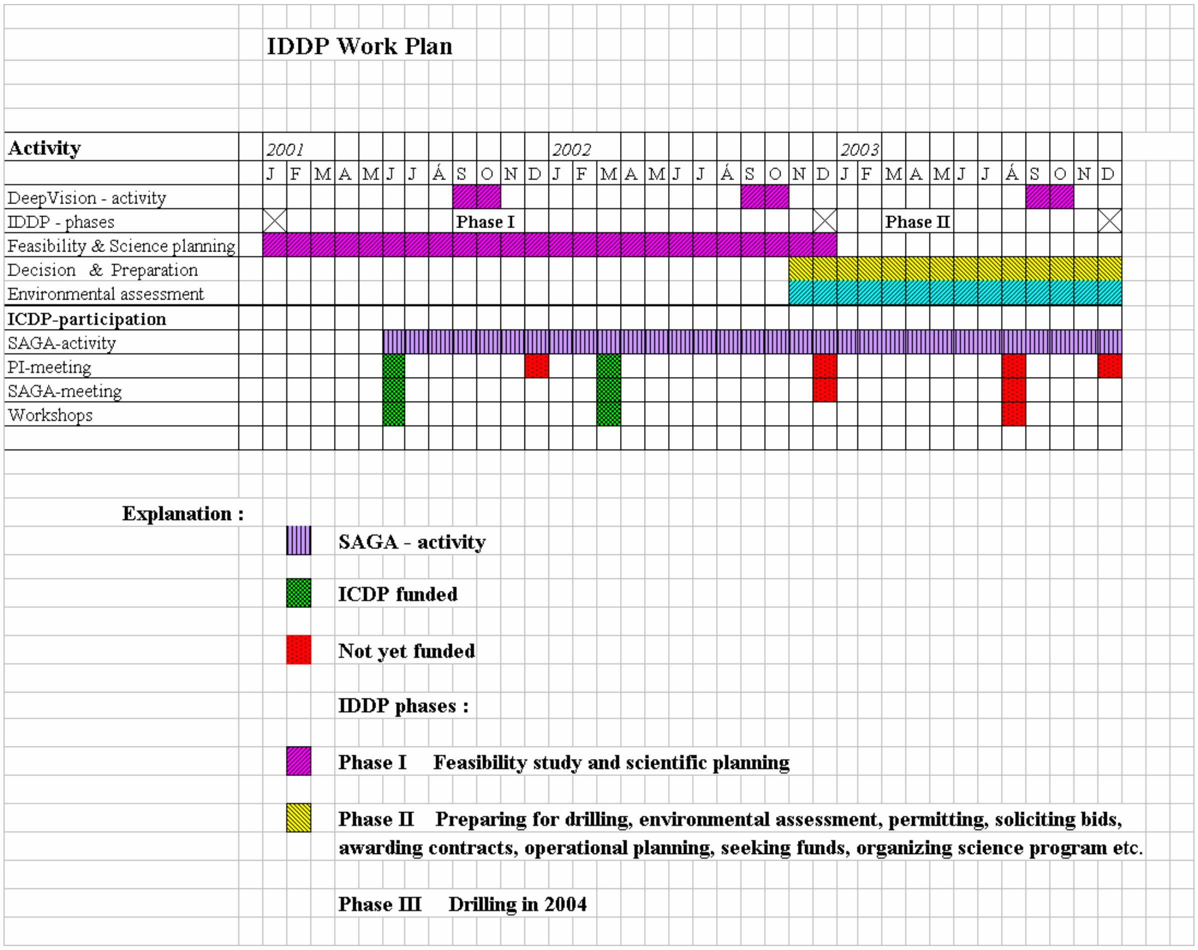
EXPECTED FLUID:
Reykjanes : 380-420°C brine, 3-5 % by weight salt; enthalpy: ~2000 kJ/kg
Hengill-Krafla: 450-500°C, dilute fluid, gas 0.1-0.2% by weight salt; enthalpy ~3000 kJ/kg

Two senarios to be studied: brine and gas

RISKS:
High uncertainty in P, T, and chemical compostion
Risk in losing the well
Environmental considerations: disposal of fluid/chemical hazards

RESULT :
Design of a downhole pilot plant - inside tubing in order to convey the fluid to the surface collect scal, corrosion coupons etc.; this solution is independent of fluid conditions
Benefits: low mass flow hence easy disposal; creates a basis for further development

TABLE 2 : Timetable



IDDP Work Plan

Activity	2001												2002												2003											
	J	F	M	A	M	J	J	Á	S	O	N	D	J	F	M	A	M	J	J	Á	S	O	N	D	J	F	M	A	M	J	J	Á	S	O	N	D
DeepVision - activity									🟪	🟪											🟪	🟪											🟪	🟪		
IDDP - phases	☒								**Phase I**															☒			**Phase II**									☒
Feasibility & Science planning	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪												
Decision & Preparation																						🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Environmental assessment																						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
ICDP-participation																																				
SAGA-activity						▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥
PI-meeting						🟩						🟥			🟩									🟥								🟥				🟥
SAGA-meeting						🟩									🟩									🟥								🟥				
Workshops						🟩									🟩																	🟥				

Explanation :

▥ **SAGA - activity**

🟩 **ICDP funded**

🟥 **Not yet funded**

IDDP phases :

🟪 **Phase I Feasibility study and scientific planning**

🟨 **Phase II Preparing for drilling, environmental assessment, permitting, soliciting bids, awarding contracts, operational planning, seeking funds, organizing science program etc.**

Phase III Drilling in 2004

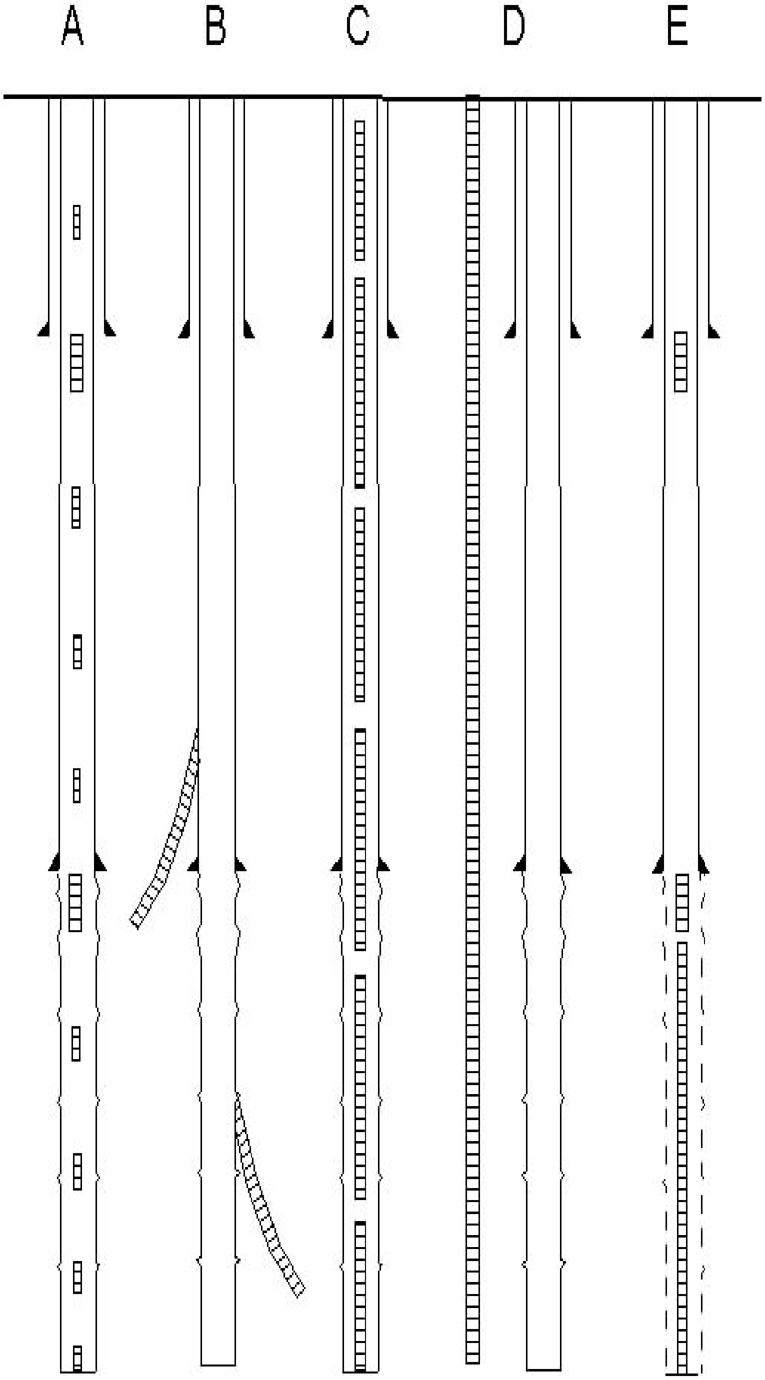


Figure 1. The 5 drilling options discussed by the panel on drilling technique. The ruled areas represent locations suggested for coring.

APPENDIX 1 :

ICDP FUNDED PI-SAGA-MEETING IN REYKJAVIK in relation to the ICELAND DEEP DRILLING PROJECT (IDDP), June 22-27, 2001.

Opening address - June 25: Minister of Industry and Commerce, Valgerður Sverrisdóttir

Guests at opening :

Kristín Karlsdóttir	**Secretary, Ministry of Industry and Commerce**
Friðrik Sophusson	**Director, Landsvirkjun**
Guðmundur Þóroddsson	**Director, Orkuveita Reykjavikur**
Júlíus Jónsson,	**Director, Hitaveita Sudurnesja**
Þorkell Helgason,	**Director General, Orkustofnun**
Vilhjálmur Lúðvíksson,	**Director, The Icelandic Research Council**
Ingvar B. Fridleifsson,	**Director, The UNU, Geothermal Training Programme**

List of Participants :

Albert Albertsson	**Deputy Managing Director, Hitaveita Sudurnesja,**
Björn Stefánsson	**Head of Power Projects, Landsvirkjun**
Einar Gunnlaugsson	**Head of Research Department ,Orkuveita Reykjavikur**
Gudmundur Omar Fridleifsson	**Senior geologist, Orkustofnun, GeoScience Division**
Seiji Saito	**Professor in Geology and Technology, Tohoku University, Japan**
Wilfred A. Elders	**Professor in Geology emeritus, University of California, USA**
Alister Skinner	**Head of Marine operation and Engineering, BGS, Scotland, UK**
Dennis Nielson	**Executive director, DOSECC, USA**
Gudio Cappetti	**Geothermal Projects Development Manager, Erga group Enel, Italy**
John Sass	**Scientist emeritus, USGS, USA**
Robert Fournier	**Scientist emeritus, USGS, USA**
Guðmundur Pálmason	**Director emeritus, Orkustofnun, GeoScience Division**
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APPENDIX 3:

ICDP FUNDED PI-SAGA-MEETING IN REYKJAVIK in relation to the ICELAND DEEP DRILLING PROJECT (IDDP), June 22-27, 2001.

WORKING GROUPS June 26th

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REPORT OF WORKSHOP No 1 OF THE ICELAND DEEP DRILLING PROJECT, NESJAVELLIR, ICELAND, MARCH 17-19, 2002

EXECUTIVE SUMMARY

The Iceland Deep Drilling Project (IDDP) is an investigation of supercritical phenomena in hydrothermal systems within the mid-ocean rift system in Iceland. Workshop No 1 of the IDDP was concerned primarily with developing the optimum strategy of meeting the difficult technical challenges of drilling and sampling wells to depths of 3.5 to 5 km and temperatures of >450°C. The workshop led to a clearer definition of the conditions likely to be encountered and developed the guidelines for planning drilling and coring. The outcome was an enthusiastic endorsement of the project by both industrial and scientific partners in the IDDP. We anticipate that the site of the first well will be chosen in the near future, allowing the specific well design to be finalized and cost estimates to be made. The next step is to make, and begin implementing, a detailed science plan with broad international participation.

INTRODUCTION

The IDDP plans to drill a series of deep boreholes to penetrate into supercritical zones thought to exist beneath three currently exploited geothermal fields in oceanic ridge-type spreading centres in Iceland. The main aim is to produce fluids for power production that have significantly higher enthalpies than are currently being utilized. Deep Vision, a consortium of Icelandic energy companies, is funding the IDDP. A feasibility study, with a budget of more than US $ 300,000, is currently under-way, examining the three candidate sites and the economic and engineering issues of drilling to greater depths and higher temperatures than are currently drilled (See the IDDP web page at www.os.is/iddp/). Deep Vision has invited the participation of the scientific community to use these wells for scientific studies that are consistent with the project, to the mutual advantage of both industrial and scientific participants. Accordingly a start-up meeting was held in Reykjavik in June of 2001, with funding from the International Scientific Continental Drilling Program (ICDP), to begin planning a scientific program. A ***Science Applications Group of Advisors*** (SAGA), with both Icelandic and international membership was formed (see Appendix 1) to develop the guidelines for a scientific program within the IDDP.

A workshop, funded by the ICDP, was held at Nesjavellir, Iceland, March 17-19th 2002, to assess the progress of the feasibility study, and to discuss the options for meeting the challenges of drilling at these high temperatures while maximizing the sampling and measurements essential to the scientific program being planned. Appendix 2 shows the Agenda of the Workshop and the List of Attendees The SAGA committee met on March 19-20th to review the input from the workshop and its significance for the scientific program. A second workshop to develop the specifics of this scientific program is planned for October 2002.

BACKGROUND

Why Study Supercritical Conditions?

The physics and chemistry of supercritical fluids in the Earth's crust are of considerable interest in understanding problems as diverse as the cooling of igneous intrusions, contact metamorphism, the formation of hydrothermal ores, and the submarine hot springs known as black smokers on mid-ocean ridges. Superheated steam produced from a fluid initially in the supercritical state can have a higher enthalpy than steam produced from an initially two-phase system. Large changes in physical properties at, and near, the critical point in dilute fluid systems can lead to extremely effective rates of mass and energy transport. Similarly, because of major changes in the solubility of minerals above and below the critical state, supercritical phenomena can play a major role in high temperature water/rock reaction and the formation of ore bodies. Hitherto, study of the supercritical phenomena has been restricted to either small-scale laboratory experiments or to investigations of "fossil" supercritical systems exposed in mines and outcrops. Furthermore mathematical modeling of the chemistry of supercritical fluids is hampered by a lack of a reliable thermodynamic database over the range of temperatures and pressures of the supercritical state.

Why Drill in Iceland?

Iceland is the largest landmass straddling a mid-ocean ridge. The tectonic setting of this diverging plate boundary results in active rifting and volcanism that provides the heat source for the well-established Icelandic geothermal industry. Very high heat flows within this active tensional regime indicate supercritical temperatures should exist at drillable depths in several places in Iceland. Temperatures greater than 300°C are commonly encountered in wells drilled to only 2 km. The likely existence of permeable regions in brittle basaltic rock at supercritical temperatures at still greater depths beneath some of these geothermal fields is inferred from the distribution of hypocentral depths of seismic activity that continues to below 5 km.

Each of the three sites selected for consideration by the IDDP displays a different stage in the tectonic development of the mid-ocean ridge. The Reykjanes site represents an immature stage of rifting with a heat source that probably is a sheeted dike swarm. Fluids produced by 2 km deep geothermal wells in this system are evolved seawater. At Nesjavellir, the Hengill central volcano is the high temperature heat source for a geothermal reservoir in a graben that has temperatures of up to 400^{o}C at 2.2 km, and is recharged by meteoric water. The Krafla high-temperature geothermal field is developed above a magma chamber in a mature, active, volcanic caldera. It produces evolved meteoric water with some addition of volcanic gases.

It is clear that the objectives of the IDDP overlap with those of drilling being considered on submarine ocean ridges by the international ocean-drilling program. Indeed Iceland might be considered as a *"Mission Specific Platform"* for drilling at a divergent plate margin.

GOALS AND ORGANIZATION OF IDDP WORKSHOP 1

Drilling to temperatures of 450°C or greater at depths of 3.5 to 5 km presents severe technical challenges compared to those faced by most other scientific drilling projects (see Table 1, Some Deep Wireline Coring Projects). Given this background it was decided that the focus of the first IDDP workshop should be on the drilling strategy required to meet the scientific objectives of the IDDP (see Appendix 2, Workshop Agenda).

Table 1: Some Deep Wireline Coring Projects (Modified from data compiled by Bernd Wundes)

Project		**Depth**		**Thermal Regime**
Iceland Deep Drilling Project (planned)	IDDP	4000-5000 m	Vertical	400-600°C
Chinese Continental Scientific Drilling	CCSD	5000 m	Vertical	Medium
French Geological Exploration for Tunnelling	ALPET.	3000 m	Deviated	Cold
Hawaii Scientific Drilling Project	HSDP	4400 m	Vertical	Cold
Japanese Unzen Drilling Project (planned)	USDP	2200 m	Deviated	Hot
Kontinental Tiefbohrung (Vorbohrung)	KTB	4001 m	Vertical	Cold
Ukraine Krivoy Rog Superdeep Borehole		5400 m	Vertical	Cold
Long Valley Scientific Drilling Program	LVEW	3000 m	Vertical	Cold
San Andreas Scientific Drilling Project	SAFOD	4200 m	Deviated	Medium

The workshop began with a review of the ultimate scientific goals of the IDDP, "*to investigate supercritical phenomena in an ocean rift setting*". This was followed by a discussion of supercritical phenomena, with dilute and saline fluids, and of the geology of the environments in which they are likely to occur at drillable depths in Iceland. Discussion followed on computer modeling of the chemistry of supercritical fluids in equilibrium with basaltic rocks.

The purpose of these discussions was to define more exactly the drilling targets we are seeking to explore from both industrial and scientific viewpoints. A discussion of the requirements of the scientific program for cores, fluids and downhole measurements followed, as input to a broad review of possible well design and coring techniques. This, in turn, provided the background for the discussion of the optimization of drilling strategies. Similarly consideration of the engineering requirements of sampling and measuring the flow characteristics of supercritical fluids led to discussion of the optimization of fluid sampling and testing systems.

The workshop then split into three panels, “Geosciences”, “Fluid Handling and Evaluation” and “Drilling”. These panels reported back to the Plenary Session of the Workshop and made recommendations to guide the progress of the feasibility study. By the time of the Science Planning Workshop in October 2002, we anticipate that site selection will have been made, and that plans for well design and sampling, and their associated costs, will be near completion.

Finally, fruitful discussions between SAGA and representatives of Deep Vision were held that emphasized their serious commitment to the IDDP.

REPORT OF THE GEOSCIENCE PANEL

The charge to the panel was to discuss geoscience issues in support of the various technical topics assigned to both the Fluid Handling and Evaluation Panel and the Drilling Panel. Development of a comprehensive detailed science program will be the purpose of the next workshop of the IDDP to be held in October 2002. One of the principal objectives of the IDDP is to establish if high-temperature (400-500^{o}C) and high-pressure crustal fluids can be extracted economically from roots of high-temperature geothermal systems. The first aim of the Geoscience Panel was therefore to help define the drilling target by specifying the likely range of conditions of fluid temperature, pressure and composition, and of lithology and permeability that might be encountered at depth in the three sites being investigated by the feasibility study. Depending on the initial salinity of the recharge water, minimum supercritical temperatures will be in the range 375 to 425^{o}C, and minimum fluid pressures in the range 225 to 350 bars. Depending on the temperature gradient this will require drilling to 3.5 to 5 km depths.

Preliminary well simulator models being carried out as part of the feasibility study indicate that temperatures of 450^{o}C or greater, at initial fluid pressures of 350 bars or less, are necessary in order prevent the fluid from entering the two-phase field liquid water plus “wet” steam, during ascent and decompression. It is possible that the steam produced in the resulting 2-phase mixture might have an enthalpy no higher than steam produced from a “conventional” geothermal well that taps a liquid water reservoir. However, the mass fraction of that steam in the 2-phase mixture that results from adiabatic decompression of supercritical fluid should be much greater than that generally produced by flashing steam from a liquid water reservoir.

The chemical composition of supercritical fluids in the Earth´s crust is different in different geological environments. In different localities in Iceland, and at different times in a given locality, supercritical fluids may have originated as meteoric water or seawater, and may contain volcanic gases evolved from magmas intruded along rifts. In addition to the extraction of heat from these fluids, another societal benefit could be extraction of metals and other valuable chemical constituents from solution.

Two major topics of fluid characterisation were discussed at the meeting: (1) likely initial compositions of the aquifer fluids and their temperatures and pressures, and (2) the corrosion and scaling potentials as the fluids depressurize and cool during ascent to the surface. Considerable attention was given to thermodynamic modeling of fluid-mineral interactions at supercritical conditions. At this time there are uncertainties regarding the actual temperature, pressure, salinity and gas content of supercritical fluids occurring in basaltic rocks. Resolving that uncertainty is one of the major goals of the

IDDP. Assuming a certain initial fluid composition, temperature, and pressure, it is possible to model with a high degree of certainty the scaling potential for some silicates, such as quartz, but with little certainty for many other minerals, such as the sulfides. The general consensus was that scaling problems would be greater in a system involving seawater, as expected at Reykjanes, as compared to more dilute water systems as at Nesjavellir and Krafla. In particular, it is expected that sulfide deposition will be more extensive from seawater as compared to dilute water systems. Also acidity due to transfer of gases from the magma heat source is known to enhance rock dissolution and in this way intensify sulfide deposition during decompression and cooling.

The Geoscience Panel recommended that reaction progress modeling should be continued to evaluate the composition of dilute and seawater fluids in basalt over the range of temperature and pressure of interest. The Panel also recommended that assessments of the composition of fluids in equilibrium with hydrothermal mineral assemblages found in basaltic rocks altered by aqueous fluids, at 300-500^{o}C and 200-1000 bars, should also be made for comparison with the fluids actually observed. This would help to determine the reliability of predictions of behavior at higher temperatures, and make more certain estimates of scaling potentials of sulfides and other minerals. At a later stage another priority should be modeling of heat and mass transfer in the supercritical state at the candidate sites for drilling.

Attention was also given to issues such as the amount of rock and fluid sampling, necessary to characterize the supercritical environment. The panel pointed out that, as the deepest geothermal wells in Iceland reach only 2.3 km, some coring should be planned between 2.5 and 3.5 km, depths where temperatures would be subcritical. This would also be a good test of the coring system employed before the higher target temperatures are reached.

Another drilling-related issue considered by the Geoscience Panel was how to recognize when supercritical conditions had been penetrated while drilling. Several approaches were suggested. The first would be to augment the “mud-logging” system normally used in geothermal drilling, looking for “kicks” in parameters such as circulation losses/gains, differences in inlet/outlet temperatures, and gas, chloride, and other chemical components of the “mud” returns. The second approach would be to use applied geothermometry during drilling by making on-site studies of core and cuttings, studying mineral assemblages and fluid inclusions. Other valuable information would be gained by deployment of high-temperature, downhole pressure, temperature, and possibly flowmeter tools.

The panel made the following general recommendations with respect to selection of the site for the first deep well:-

i) Drill where the supercritical zone is likely to be at the lowest pressure and shallowest depth. Not only does this reduce the drilling costs but should also lead to higher enthalpy of the discharged fluid at the wellhead. It should also lead to lower concentrations of dissolved solids in the fluid, and possibly better permeability. However it could lead to higher HCl than would be the case for production at higher pressure.

ii) Select a geothermal system of low salinity to minimize problems of scaling, corrosion and acidity.

iii) Avoid lithologies with rocks of silicic and intermediate composition as they behave plastically at lower temperatures than do basalts, and are likely either to have poorer permeability or to contain fluids and gases at, or near, lithostatic pressures.
iv) Drill where indications in the shallower reservoir and geophysical studies suggest the existence of permeabilty at the depth of the supercritical zone.
v) Play safe by siting the first deep well of the series where the available data are adequate to meet the above criteria so that the possibilty of failure is least.

REPORT OF THE FLUID HANDLING AND EVALUATION PANEL

The charge to the panel was to discuss the approach being used by the feasibilty study to design a fluid handling system, and the implications of that design for the science program and for the drilling strategy. Given the uncertainties of investigating a fluid from a hitherto unexplored deep geothermal aquifer, with unknown pressure, temperature, chemistry and permeability, it is premature to begin designing a pilot plant. The immediate need after drilling into supercritical conditions is to produce the fluid to the surface for sampling and analysis while protecting the well from scaling or corrosion that might prevent its future use. It is possible that downhole samplers could be deployed, however sufficient production is necessary to remove contaminants introduced by drilling. Another issue is how to isolate production from different zones in a long open interval, and, if necessary, prevent downhole inter-formational blow-outs.

The concept proposed by the feasibility study is to use a removable inner liner reaching to the producing aquifer. This “pipe” is intended both to protect the well casing and to allow inspection of the effects of corrosion and scaling at different depths after removal. Flow would be measured at the well head and attempts would be made to measure pressure/temperature profiles downhole. Samples for chemical analysis would be collected over a range of flow conditions, giving vital information on the reservoir conditions.

The Panel met jointly with the Geoscience Panel to discuss how the chemistry of the supercritical fluids could be predicted, in terms of non-condensable gases and dissolved solids, either by modeling or by analogy with known geological situations. The possible extraction of hydrogen and/or other salable materials from the fluid was discussed. At present, 200 tonnes of hydrogen are vented annually from the Nesjavellir geothermal field and 100 tonnes from the Namafjall field near Krafla. Methods of splitting hydrogen sulfide to yield hydrogen and sulfur exist.

Another issue discussed was the possibility of *in situ* extraction of metals from fluids similar to those that occur in black smokers on ocean ridges. Of the three sites being investigated by Deep Vision, the Reykjanes Peninsula would be the most likely to have suitable chemistry for this approach to be considered. A downhole process of metal extraction from supercritical fluid that would require a wide diameter hole was briefly discussed.

The recommendations of the panel were:
i) The concept of producing through a solid liner (the “pipe”) seems prudent,although there are a number of technical issues to discuss, such as metallurgy and diameter of the liner, and the specifications of downhole valves, liner hangers, and expansion collars, etc, and the disposal of the produced fluids.
ii) Heating of the pipe, for example by induction, may be necessary.

iii) Downhole valve assembly is preferable to enable replacement of the pipe.
iv) Calculations were presented to the panel, which indicate that the temperature of the fluid in the formation should exceed 450°C at an initial fluid pressure less than 350 bars for the steam to offer enthalpy advantages over steam from wells of conventional depth.
v) It appears that up to an order of magnitude more electricity might be generated by the fluid from a well producing from a supercritical zone than is produced from a conventional steam-water well.

REPORT OF THE DRILLING PANEL

The charge to the panel was:-
1) to review the difficulties of drilling in basalts at >450^{o}C at depths of 3.5 to 5 km,
2) to discuss experiences of drilling in other high-temperature regimes,
3) to examine different coring systems that could be used,
4) to make recommendations to Deep Vision on optimising the design and drilling of a "dual purpose" well that meets both scientific and industrial objectives safely and economically.

Fruitful discussions were held among panel participants with a diversity of experience in drilling in different environments, and with representatives of organizations that have developed different approaches to drilling and coring. The Panel continued from its June 2001 meeting by considering four options for adding science coring in two different sizes of production wells (Figure 1, Well Profiles A & B). Well Profile A has a 9 5/8 inch production casing to 3500 m, whereas Well Profile B has a 9 5/8 inch casing to 2400 m with a 7 inch production casing to 3500 m. The upper part of Profile B (to 2400 m) is the design currently used in standard production wells used in the geothermal fields of the Reykjanes Peninsula. It is estimated that drilling, coring and reaming to a nominal depth of 5000 m would take about 250 days.

Based on presentations from representatives of DOSECC, AQUATIC (CCS), and BOHRGESELLSCHAFT RHEIN-RUHR (BRR), three different coring systems were considered for evaluation to core in the interval 2400 m to 3500m, and for continuous coring below 3500 m (Table 2, Four Options for Coring). These use two modes of coring; (a) "Large Diameter" diameter coring, with large diameter core, large kerf, and (b) "Small Diameter" coring with smaller core, small kerf, and low mud volumes (Table 3, Technical Data for Deep Wireline Coring). It was shown that either system produces insignificant well cooling as coring produces less than a tenth of the mudflow used in conventional rotary drilling.

Each of the technologies available provides distinct advantages and drawbacks (Table 4, Tradeoffs between Small Diameter- and Large Diameter Hole). The choice will be dictated primarily by the required well diameter for flow testing and logging and also by such parameters as maximum hookload availability and well-safety considerations, and costs. The specific details of the well design like casing depths, cementing plans, and coring method(s) are dependent on completion of the pre-feasibility study. If funds allowed, it would be desirable to evaluate at least two of the available technologies by coring parts of the interval between the currently exploited hydrothermal reservoir (2,400 m) and the bottom of the cased part of the well (3,400 m, Figure 1). The technique that performs best in that interval would then be the preferred choice for coring into the supercritical zone. In the likely event that the latter approach proves economically unfeasible, a coring sub-contractor will be chosen on the basis of cost and technical merit.

The above approach to designing the first IDDP well combines tried and tested geothermal rotary drilling technology, used in Iceland for many years, with a wireline coring approach that has been deployed successfully in geothermal exploration and development in Indonesia and elsewhere. The conservative design is illustrated by well profile A (Figure 1), with a string of 13 3/8 inch casing cemented in to a depth somewhat greater than the typical (2,000 m) Iceland geothermal reservoir, nominally 2,400 m. Well profile B represents the current standard geothermal well completion with a 9 5/8 inch casing string cemented in at the top of the production zone. The decision on which approach to use will be dictated by the commercial and engineering requirements and cost considerations of Deep Vision.

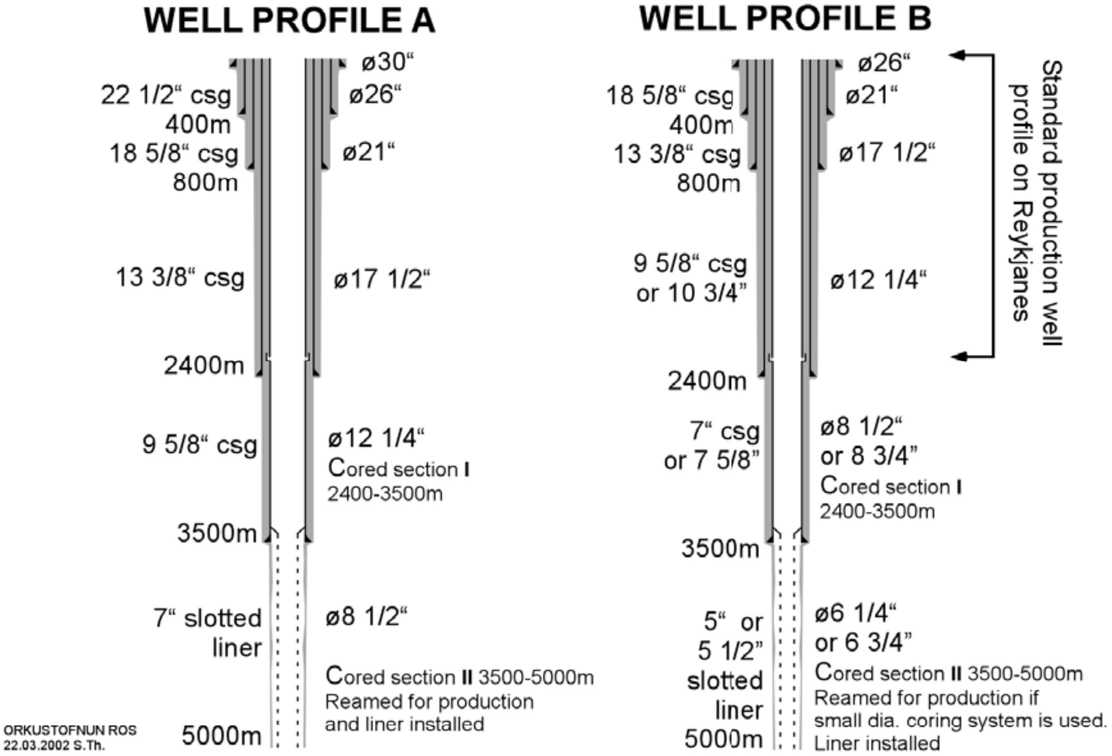

Figure 1. Well profile A and Well Profile B

The idea is that science drilling would begin from the nominal 2,400 meter depth (actual depth will be determined by local conditions at whichever site is chosen). In the case of both Well Profile A or B, a “bushing string” of technical casing will be tied back to the surface, and a wireline corehole will be drilled through the conventional reservoir interval (Figures 2A & 2B) to near the top of the supercritical zone, nominally 3,500 m in Figure 1. This hole will be, in turn, reamed to an appropriate diameter, necessary logging and testing will be performed, and then coring resumes until the desired temperature (in the range of 400 to 500° C) is reached (hopefully at less than the nominal value of 5,000 m shown in Figure 1). Another string of casing will be tied back to the surface and cemented in (Figure 2). A slotted liner will have to be run in the open hole section and a “pipe” run to surface to meet the requirements of the fluid handling and evaluation panel. Fluid sampling and testing will be conducted, and the supercritical regime evaluated. This stage concludes the scientific well testing and sampling. Then, depending on the results of the evaluation of the supercritical regime, the lower part of the well will either be plugged and abandoned, or reamed and fitted with a production liner to facilitate large scale production of fluid both for commercial purposes and more comprehensive scientific and technical studies of fluid properties.

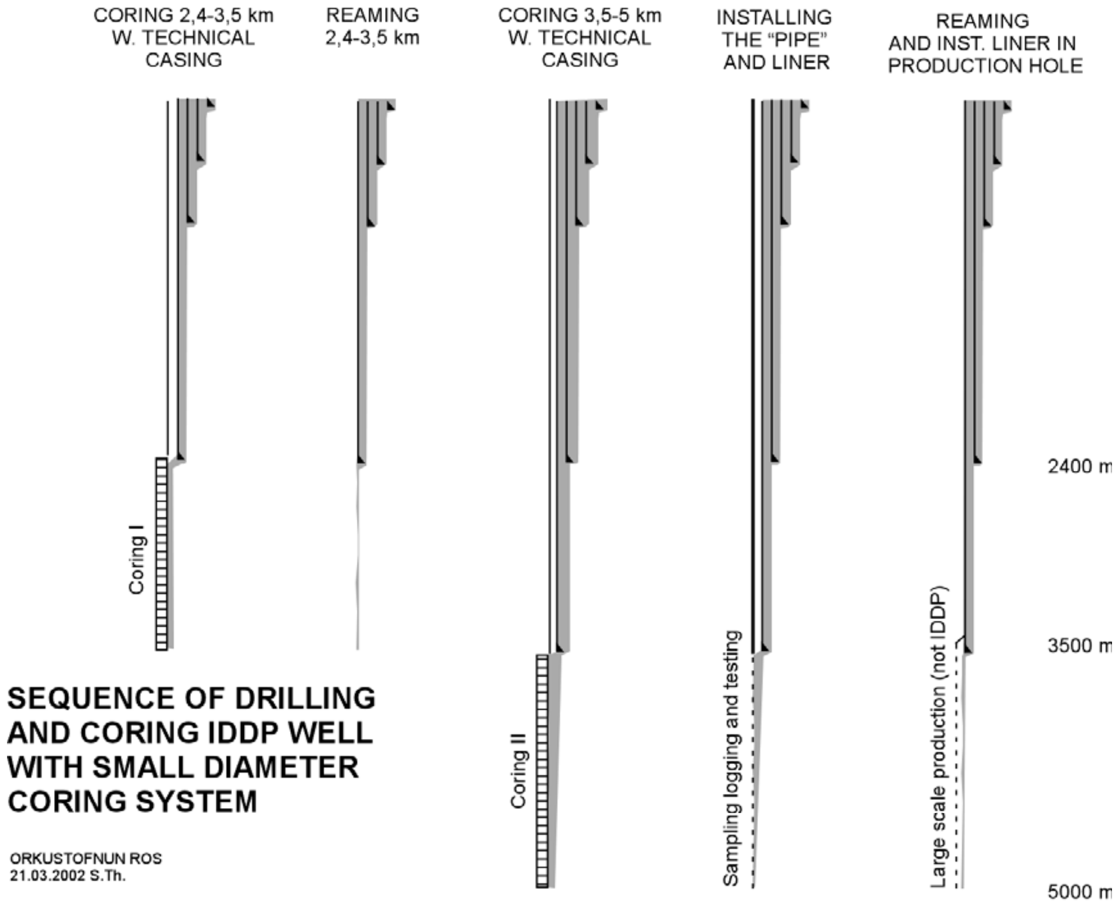

Figure 2 A. Sequence of drilling and coring with small diameter coring

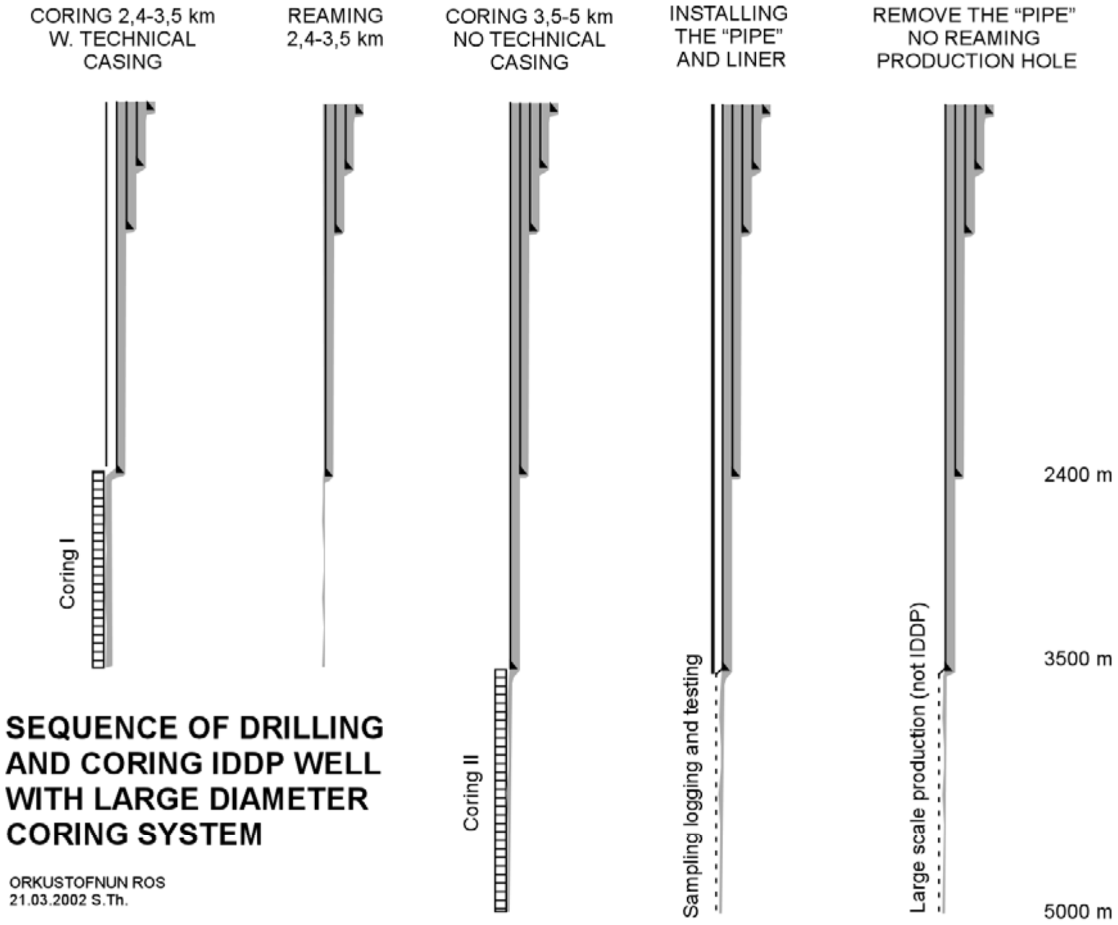

Figure 2B. Sequence of drilling and coring with large diameter coring

Table 2. Four options for coring in wells A and B

Four Options	Rig Capacity	Production Casing	Last Hole Dia	Core Size	Hole Size		Cored Sec km	Option
Small Diameter Hole	180 ton	7"	6 1/4"	2.4"	3 7/9"	DOSECC	2.3-3.4 3.4-5.0	**op-1**
		7 5/8"	6 3/4"	4.0"	6 3/4"	BRR	2.3-3.4 3.4-5.0	**op-2**
Large Diameter Hole	250 ton	9 5/8"	8 1/2"	2.6-3.1"	8 1/2"	CCS	2.3-5.0	**op-3**
				2.4"	3 7/9"	DOSECC	2.3-5.0	
				4.0"	6 3/4"	BRR	2.3-5.0	
				2.6-3.1"	8 1/2"	CCS	3.4-5.0	**op-4**
				2.4"	3 7/9"	DOSECC	3.4-5.0	
				4.0"	6 3/4"	BRR	3.4-5.0	

Table 3. Technical data for deep wireline coring systems (ref. Bernd Wundes)

Technical Data for Deep Wireline coring Systems

ITEM	**CCS** **Aquatic**	**ICDP-WL** **(Micon)**	**SK5** **BRR**	**DOSECC**	
				Top Str as WLDP	**Cr Brl** and WLDP
Last Casing or	9 5/8"	7"	7 5/8"	5"x7.53 mm	
temporary working string					
Hole Diameter	222 mm	155.6 mm	171.5 mm	96 mm	
Core Diameter	80 mm	94 mm	101.6 mm	63.5 mm	
Drillpipe Type	ADP	Special	Special	Hydril	HMCQ
Pipe OD, mm	164-168	139,7	139,7	88,9	88,9
Tooljoint OD, mm	197	146	162	99,06	88,9
Pipe ID, mm	146	123,5	123,7	74,73	77,8
Tooljoint ID,mm	144	110	123,5	76	77,8
Traction Tensile,MN	>3.3	>3.0	>3.1	0,93	0,42
Makeup Torque, Nm	30.000	21.000	25.000	4.339	2.000
Mudflow rate, l/min	700-1500	175	250	100	100
Mud Velocity, Pipe OD,m/s	0.75-1.5	0,79	0,54	0.44	0.79
Mud Velocity, t-joint OD, m/s	1.9-3.1	1,29	1,68	0.72	1,62
Weight in air, kg/m	23,5	29	30	13.73	9,81
Depth rating, m for SF=2	9000	6358	6358	6560	2634
Material Grade pipe	Aluminum	G105	P110	S125	C1541
		30CrNiMo8V	SAE4145 Hmod	Thread cut in wall	

Table 4 : Tradeoffs between small diameter- and large diameter hole coring systems

Hole type :	Cooling Effect	Money	Casing/cementing	Core Diameter	Diameter of the "pipe"
Small Diameter	Minus (low flow rate)	Plus	Minus (Narrow annulus)	64 mm	Minus
Large Diameter	Plus (for CCS)	Minus (Large hookload)	Plus	80-102 mm	Plus
Qualitative judgment. Numbers need to be developed. Issues include %core recovery,high temp capability, and degree of cooling.					

GENERAL CONSIDERATIONS AND FUTURE PLANS

If Deep Vision's long term goals of economic energy production and mineral extraction from supercritical geothermal resources are realized, the approach could improve the economics of high-temperature geothermal resources world-wide. This will require a great deal of technology development over the coming decades. However the first step is to drill in search of the supercritical fluids. The wide-ranging discussions at the workshop allayed doubts that the IDDP wells can be drilled and sampled, using available technology and at reasonable costs. The feasibility study being carried out by the National Energy Authority of Iceland and its subcontractors appears to be well on track.

Discussions with representatives of Deep Vision were very productive. They reaffirmed the commitment of the consortium to the IDDP and their willingness to facilitate scientific studies. Meetings with the power companies will take place shortly to present ideas on the preferred well design and on site selection. Choice of the site for the first deep well will depend partly on business decisions on financing and partly on environmental permitting. However, the long term expectation is that deep wells will be drilled at all three sites by the power companies, and that these wells will be made available for deepening and coring for scientific studies. From a scientific viewpoint all three sites are appealing.

This prospect opens up the opportunity for a very comprehensive scientific program investigating the anatomy of a mid-ocean rift zone, by tying together land–based and ocean-based deep borehole studies with complementary geological and geophysical studies. The next step is to organize a workshop on the science to be done in connection with the first deep hole, while developing plans for a much more comprehensive and long-term program.

APPENDIX 1 IDDP - Membership of SAGA :

Stefán **Arnorsson**		University of Iceland
Jón Örn **Bjarnason**		Orkustofnun, Geoscience, Iceland
Guido **Cappetti**		Erga Gruppo Enel, Italy
Wilfred A**. Elders**	PI	University of California, USA
Gudmundur Ó. **Fridleifsson**	PI	Orkustofnun, Geoscience, Iceland
Robert O. **Fournier**		USGS, USA
Valdemar K. **Jónsson**		University of Iceland
Runólfur **Maack**		VGK Engineering, Iceland
Dennis **Nielson**		DOSECC, USA
Gudmundur **Palmason**		Orkustofnun, Geoscience, Iceland
Seiji **Saito**	PI	Tohoku University, Japan
John **Sass**		USGS, USA
Alister **Skinner**		BGS, Scotland U.K.
Valgardur **Stefansson**		National Energy Authority, Iceland

Appendix 2 IDDP / ICDP Workshop 1 Agenda

OVERVIEW

	17 March 2002	18 March	19 March	20 March	21 March
	Sunday	**Monday**	**Tuesday**	**Wednesday**	**Thursday**
	Workshop begins			*Departure to Europe*	*Departure to Europe and Japan*
09:00	Welcome / IDDP introduction	High-T logging and sampling	Panels continue	**SAGA -**	**PI-meeting**
09:15	Workshop goals	(Cancelled for unforseen reason)		**meeting**	**complete**
09:30	Supercritical phenomena	Producing through the "pipe"		Review of	**SAGA report**
10:00	Supercritical phenomena continued	Casing Design		reports	
10:40	***Coffee 20 min***	***10:10 Coffee 20 min***	***Coffee 20 min***	***Coffee 20 min***	
11:00	Feasibility Report - 3 presentations	10:30 Ocean Hydrothermal Res.	**Prelim. Report within Panels**	topic groups	
12:00	ICDP - Introduction	10:50 Interface Science-Drilling	Discussion		**PI-meeting ends**
		11:10 Organization of panels			
12:30	***Lunch***	***Lunch***	***Lunch***	***Lunch***	***Lunch***
13:30	Supercritical phenomena cont.	**Split into Panels**	**Plenary session**	SAGA report	
14:10	Case studies from active high-T	1 Drilling Technology	Final panel reports,	writing	
14:30	fields > 340°C 4-5 presentations	2 Fluid Handling	discussions and		
15:00	Improving borehole stability	3 GeoSciences	recommendations		
15:30	***Coffee 20 min***	***Coffee 20 min***	Earliest departure	*Departure*	*Departure to USA*
16:10	Rig selection / the Jotun rig	Panels continue	*to USA & Europe*	*to USA & Europe*	
16:30	The DOSECC hybrid coring system				
16:50	Coring technology (BRR)				
17:10	Improved Drill Bits			**SAGA -**	
17:30	Complete Coring System (CCS)				
18:00	**end**		**Workshop ends**	**meeting ends**	
18:30	Reception hosted by Orkuveita Reykjavikur				
19:30	Dinner			**PI-meeting**	

	Sunday 17 March 2002		**Chairman**	**DETAILS**
09:00	Welcome / IDDP introduction	Gudmundur Omar Fridleifsson	**Seiji Saito**	15 min
09:15	Workshop goals	Wilfred A. Elders		15 min
09:30	Supercritical phenomena-geochem.	Robert O. Fournier		30 min
10:00	Supercritical phenomena-geochem.	H. Armannson & G. Gislason		20 min
10:20	Supercritical phenomena-geochem.	Mark Reed		20 min
10:40	***Coffee 20 min***			
11:00	Feasibility report - Drilling Technique	Sverrir Thorhallsson	**Gudmundur Pálmason**	20 min
11:20	Feasibility report -Fluid handling	Runólfur Maack		20 min
11:40	Feasibility report - Geosciences	Gudmundur Omar Fridleifsson		20 min
12:00	ICDP - What is ICDP ?	Ulrich Harms		20 min
12:30	***Lunch***			
13:30	Supercritical phenomena at < 3,5 km	Gudmundur Omar Fridleifsson	**Valgardur Stefánsson**	20 min
13:50	Supercritical phenomena at > 3,5 km	Dennis Bird		20 min
14:10	Kakonda hostile fluid/rock T>340°C	Seiji Saito		20 min
14:30	Geysers hostile fluid/rock T>340°C	Dennis Nielson		20 min
14:50	NJ-11/KG-4 hostile fluid/rock T>340°C	Benedikt Steingrimsson		20 min
15:10	Salton Sea hostile fluid/rock T>340°C	W.A.Elders		20 min
15:30	Improving borehole integrity and stability	Vincent Maury		20 min
15:50	***Coffee 20 min***			
16:10	Rig selection / the Jötunn rig	Thór Gíslason	**John Rowley**	30 min
16:40	The DOSECC hybrid coring system	Marshall Pardey		30 min
17:10	Coring technology (BRR)	Bernd Wundes		30 min
17:40	Discussion			
18:00	**Break - Reception 18:30 - Dinner 19:30**			
	Monday 18 March 2002			
09:00	Improved Drill Bits	Mike Thigpen		20 min
09:20	Complete Coring System (CCS)	Mikhail Gelfgat		30 min
09:50	Producing through the "pipe"	Jón Örn Bjarnason	**Stefán Arnórsson**	20 min
10:10	Casing Design	Matthias Matthiasson		20 min
10:30	***Coffee 30 min***			
11:00	Ocean Hydrothermal Resources	Daniel Fraser	**Robert Fournier**	20 min
11:20	Interface Science-Drilling	John Sass		20 min
11:40	Organization of panels - open discussion	Wilfred Elders		20 min
12:00	***Lunch***			
13:30	**Split into Panels**			

Appendix 3 List of Attendees

No.	Participants	Affiliation	Location
1	Wilfred A. Elders	University of California	Riverside, USA
2	Seiji Saito	Tohoku University	Sendai, Japan
3	John Sass	USGS	Flagstaff, USA
4	Robert O. Fournier	USGS	Menlo Park, USA
5	Dennis Nielson	DOSECC	Salt Lake City, USA
6	Mark Reed	University of Oregon	Eugene, USA
7	Dennis Bird	Stanford University	Stanford, USA
8	John Rowley	Pajarito Enterprises.	Los Alamos, USA
9	Mary Rowley	Pajarito Enterprises.	Los Alamos, USA
10	Daniel Fraser	University of Manitoba	Winnipeg, Canada
11	Mikhail Gelfgat	Aquatic Company	Moscow, Russia
12	Vincent Maury	GEOMEC, Scientific Adviser	Idron, France
13	Marshall Pardey	QD Tech, Inc	Salt Lake City, USA
14	Bernd Wundes	Bohrgesellschaft Rhein-Ruhr	Dortmund-Kurl, Germany
15	Mike Thigpen	Varel P.D.Products	Houston, USA
16	Ulrich Harms	ICDP	Potsdam, Germany
17	Gord Klimenko	University of Manitoba	Canada
18	Nic Nicols	Baker Hughes International	USA
19	Tor Tan Eriksen	Baker Hughes International	Stavanger, Norge
20	Gudmundur Pálmason	Orkustofnun GeoScience	Reykjavik, Iceland
21	Stefán Arnórsson	University of Iceland	Reykjavik, Iceland
22	Valgardur Stefánsson	*National Energy Authority*	Reykjavik, Iceland
23	Jón Örn Bjarnason	Orkustofnun GeoScience	Reykjavik, Iceland
24	Runólfur Maack	VGK-engineering	Reykjavik, Iceland
25	Gudmundur Ómar Fridleifsson	Orkustofnun GeoScience	Reykjavik, Iceland
26	Einar Gunnlaugsson	Orkuveita Reykjavikur	Reykjavik, Iceland
27	Albert Albertsson	Hitaveita Sudurnesja	Reykjavik, Iceland
28	Björn Stefansson	Landsvirkjun	Reykjavik, Iceland
29	Sverrir Thórhallson	Orkustofnun GeoScience	Reykjavik, Iceland
30	Ólafur G. Flóvenz	Orkustofnun GeoScience	Reykjavik, Iceland
31	Benedikt Steingrímsson	Orkustofnun GeoScience	Reykjavik, Iceland
32	Ásgrímur Gudmundsson	Orkustofnun GeoScience	Reykjavik, Iceland
33	Grímur Björnsson	Orkustofnun GeoScience	Reykjavik, Iceland
34	Halldór Ármansson	Orkustofnun GeoScience	Reykjavik, Iceland
35	Knútur Árnason	Orkustofnun GeoScience	Reykjavik, Iceland
36	Ingi Th. Bjarnason	Science Institute, Univ.of Iceland	Reykjavik, Iceland
37	Gestur Gíslason	Orkuveita Reykjavikur	Reykjavik, Iceland
38	Claus Ballzus	VGK Engineering	Reykjavik, Iceland
39	Matthías Matthíasson	VGK Engineering	Reykjavik, Iceland
40	Teitur Gunnarsson	VGK Engineering	Reykjavik, Iceland
41	Kristinn Ingason	VGK Engineering	Reykjavik, Iceland
42	Thór Gíslason	Iceland Drilling Ltd.	Reykjavik, Iceland
43	Sturla Fanndal	Iceland Drilling Ltd.	Reykjavik, Iceland
44	Bjarni Gudmundsson	Iceland Drilling Ltd.	Reykjavik, Iceland
45	Árni Gunnarsson	Landsvirkjun	Reykjavik, Iceland
46	Bjarni M. Júlíusson	Landsvirkjun	Reykjavik, Iceland
47	Bjarni Pálsson	Landsvirkjun	Reykjavik, Iceland
48	Geir Þórólfsson	Hitaveita Sudurnesja	Reykjavik, Iceland
49	Thorbjörn Karlsson	University of Iceland	Reykjavik, Iceland

	Invited guests	Affiliation	Location
50	Friðrik Sophusson	Landsvirkjun	Reykjavik, Iceland
51	Agnar Olsen	Landsvirkjun	Reykjavik, Iceland
52	Bjarni Bjarnason	Landsvirkjun	Reykjavik, Iceland
53	Gudmundur Þóroddsson	Orkuveita Reykjavíkur	Reykjavik, Iceland
54	Ásgeir Margeirsson	Orkuveita Reykjavíkur	Reykjavik, Iceland
55	Ingólfur Hrólfsson	Orkuveita Reykjavikur	Reykjavik, Iceland
56	Júlíus Jónsson	Hitaveita Sudurnesja	Reykjavik, Iceland
57	Bent Einarsson	Iceland Drilling Ltd.	Reykjavik, Iceland
58	Þorkell Helgason	National Energy Authority	Reykjavik, Iceland
59	Valgerður Sverrisdóttir	Minister of Industry and Commerce	Reykjavik, Iceland
60	Þorgeir Örlygsson	Permanent Secretary, IVR (MIC)	Reykjavik, Iceland
61	Vilhjálmur Lúdvíksson	The Icelandic Research Council	Reykjavik, Iceland
61	Sveinbjörn Björnsson	National Energy Authority	Reykjavik, Iceland
62	Ingvar B. Friðleifsson	UNU-Geothermal Training Program	Reykjavik, Iceland
63	Magnús Ólafsson	Orkustofnun GeoScience	Reykjavik, Iceland
64	Kristján Saemundsson	Orkustofnun GeoScience	Reykjavik, Iceland

REPORT OF WORKSHOP No. 2 OF THE ICELAND DEEP DRILLING PROJECT, NESJAVELLIR, ICELAND, OCTOBER 13-15, 2002

EXECUTIVE SUMMARY

The Iceland Deep Drilling Project (IDDP) is an investigation of supercritical phenomena in hydrothermal systems within the mid-ocean rift system in Iceland. This study will require drilling wells and sampling fluids and rocks to depths of 3.5 to 5 km and at temperatures of 400-600°C (See the IDDP web page at www.os.is/iddp/). Workshop No. 2 of the IDDP was primarily concerned with formulating a comprehensive science plan and discussing research proposals submitted by the international science community to participate in the IDDP. About 40 separate scientific proposals were considered at this workshop.

Workshop No. 1, the previous workshop in the series, was held in March 2002 and was concerned with optimising the strategy of drilling into and sampling supercritical conditions. That workshop led to a clearer definition of the conditions likely to be encountered and developed guidelines for planning the necessary drilling, coring and fluid sampling. Workshop No. 2, on the other hand, provided the framework for detailed planning of a scientific program integrated with the drilling and sampling strategy. The outcome was an enthusiastic endorsement of the project by both industrial and scientific partners.

Workshop No 2 was followed by a meeting of SAGA, the science advisory group of the IDDP. Specific recommendations of the SAGA meeting included (a) Performing an immediate review of existing geothermal wells in Iceland that could be utilised by the IDDP for scientific studies. (b) Discussing opportunities for drilling and sampling of pilot holes to obtain scientific information and to test technologies for later use in the hot, hostile environment of the deep boreholes that will be drilled by the IDDP. (c) Continued planning of and preparation for, the long-term program of deep drilling.

INTRODUCTION

The IDDP plans to drill a series of deep boreholes to penetrate into supercritical zones thought to exist beneath three currently producing geothermal fields in oceanic ridge-type spreading centers in Iceland. Deep Vision, a consortium of Icelandic energy companies, is partially supporting the IDDP. The main aim of the consortium is to produce fluids for electrical power production that have significantly higher enthalpies and flow rates than are currently available to the worldwide geothermal industry. If such enormous gains in energy output from supercritical reservoirs can be developed, it would enable the geothermal energy industry to exceed current estimates of its potential for meeting long-term energy demand by a substantial amount, not only in local or regional markets, but globally. Current estimates of potential geothermal contributions to global energy demand are in the range of a few percent of total installed electrical power. A five- to ten-fold increase in energy output per well from high-temperature geothermal reservoirs would make the economics of geothermal energy more competitive globally, particularly in conjunction with a hydrogen-fueled transportation system in countries like

Iceland that lack sources of hydrocarbon fuels. Therefore, the success of this project can have important environmental as well as scientific benefits.

Deep Vision is conducting a feasibility study, with a budget of more than US $500,000, to examine three candidate sites in Iceland and to consider the economic and engineering issues of drilling to greater depths and higher temperatures than are currently drilled. Deep Vision has invited the participation of the scientific community to use these wells for scientific studies that are of mutual advantage to both industrial and scientific participants. Accordingly a start-up meeting was held in Reykjavik in June of 2001, with funding from the International Scientific Continental Drilling Program (ICDP), to begin planning a scientific program. A ***Science Applications Group of Advisors*** (SAGA), with both Icelandic and international membership was formed (see Appendix 1) to develop the guidelines for a scientific program within the IDDP.

Workshop No. 1, funded by the ICDP, was held at Nesjavellir, Iceland, March 17-19th 2002, to assess the progress of the feasibility study, and to discuss the options for meeting the challenges of drilling at high temperatures while maximizing the sampling and measurements essential to the scientific program. That workshop began with presentations on the pressures, temperatures, fluid characteristics, lithologies and reservoir properties expected in supercritical zones underlying geothermal fields in Iceland. This was followed by a wide-ranging discussion by international drilling experts about possible drilling strategies and costs, leading to guidelines for planning the operational program of the IDDP.

This document is a report of Workshop No. 2, also supported by the ICDP, that focused on the science program, held at Nesjavellir on October 13-15, 2002. About 70 participants, guests and observers were present. Appendices 2 & 3 show the Agenda of the Workshop and the List of Attendees. Apart from Icelanders, participants came from Japan, New Zealand, Italy, France, Germany, Norway, Canada and USA. The SAGA committee met on October 16-17th to review the input from Workshop No. 2 and to discuss integration of the science program with the overall IDDP drilling program.

BACKGROUND

Why Study Supercritical Conditions?

The physics and chemistry of supercritical fluids in the Earth's crust are of considerable interest in understanding problems as diverse as the cooling of igneous intrusions, contact metamorphism, the formation of hydrothermal ores, and submarine hot springs on mid-ocean ridges, known as black smokers. Superheated steam produced from a fluid in the supercritical state can have a higher enthalpy than steam produced from a two-phase system. Large changes in physical properties at, and near, the critical point in dilute fluid systems can lead to extremely effective rates of mass and energy transport. Similarly, because of major changes in the solubility of minerals above and below the critical state, supercritical phenomena play a major role in high temperature water/rock reaction, and the formation of ore bodies. Hitherto, study of supercritical phenomena has been restricted to either small-scale laboratory experiments or to investigations of "fossil" supercritical systems in boreholes, mines and outcrops. Furthermore mathematical modeling of the chemistry of supercritical fluids is hampered by a lack of a reliable thermodynamic database over the range of temperatures and pressures of the supercritical state.

Why Drill in Iceland?

Iceland is the largest landmass straddling a mid-ocean ridge. This diverging plate boundary results in active rifting and volcanism that provides the heat source for a geothermal industry that plays an important role in the economy and quality of life in Iceland. Very high heat flows within this active tensional regime indicate supercritical temperatures should exist at drillable depths in several places in Iceland. Temperatures greater than 300°C are commonly encountered in wells drilled to only 2 km. The likely existence of permeable regions in brittle basaltic rock at supercritical temperatures at still greater depths beneath some of these geothermal fields is inferred from the distribution of hypocentral depths of seismic activity that continues to below 5 km. For example, seismicity is observed below 5 km depth in the area of the Hengill volcano where the temperature should certainly be higher than the critical temperature. A low value of the ratio V_p/V_s is also observed in the Hengill area. A temperature of 380 °C was measured in a feed zone at 2200 m depth in well Nesjavellir No. 11, drilled in 1985 on the northern side of the volcano. This feed zone caused an underground blowout for about one week due to inter-zonal flow from the depth of 2200 m up to the level of 1100 m where the fluid exited into the formation.

The three sites selected for consideration by the IDDP display different stages in the tectonic development of the mid-ocean ridge. The Reykjanes site represents an immature stage of rifting with a sheeted dike complex as a heat source. Fluids produced by 2 km deep geothermal wells in this system are evolved seawater. At Nesjavellir, the Hengill central volcano is the heat source for a geothermal reservoir in a graben recharged by meteoric water. The Krafla high-temperature geothermal field is developed above a magma chamber in a mature, active caldera. It produces evolved meteoric water with some addition of volcanic gases.

It is clear that the objectives of the IDDP overlap with those of drilling being considered on submarine ocean ridges by the international ocean-drilling program. Indeed Iceland might be considered as a *"Mission Specific Platform"* for drilling at a divergent plate margin. . There are clear logistic advantages to drilling on land rather than at sea. Similarly, because of its location on the Mid-Atlantic Ridge, at the center of a Large Igneous Province, Iceland is perhaps the most attractive site world-wide for drilling in support of investigations that address a wide range of world-class scientific questions involving active igneous and hydrothermal processes at divergent plate margins. These include the formation of ophiolites, and the hydrothermal activity leading to ore formation and black smokers.

GOALS AND ORGANIZATION OF IDDP WORKSHOP No. 2

This project takes advantage of the unique geologic setting of Iceland to gain a deeper understanding of fundamental processes that lead to creation of energy resources and mineral deposits. Specifically this project will drill and investigate an accessible high-temperature, magma-hydrothermal system within an ocean-spreading centre on land, to a depth that reaches into the realm of supercritical phenomena. The outcome of Workshop No 1 was reassurance that, in spite of the difficulties, drilling and sampling supercritical conditions in Iceland can be carried out safely and economically. Workshop No 2 reviewed the progress of the feasibility study, discussed a wide range of exciting scientific studies, and then split into panels to discuss (A) Rock studies (B) Fluid studies, (C) Reservoir property studies, and (D) Technical issues.

REPORT OF THE PANEL ON ROCK STUDIES

The purposes of the proposed petrological and geochemical studies are to :
(1) determine the protoliths and the volcanological, hydrothermal and tectonic history of the site(s) chosen for deep drilling. This is relevant to elucidating the formation of ophiolite sequences and ocean crust, and the volcanic processes, magma evolution and fluid movement at spreading centers.
(2) determine mineral parageneses and calculate mineral-fluid equilibria in the subcritical to supercritical regions. The geochemical, mineralogic, and geophysical data will be used to evaluate solution-mineral equilibria under both subcritical and supercritical conditions. Mineralogic phase relations and parageneses will be combined with thermodynamic properties of mineral components and fluids, to compute chemical affinities of pH and redox sensitive reactions. This will provide a basis for developing reactive mass transfer models.
(3)evaluate mass transfer. The effects of protolith (compositional as well as petrophysical) properties, of temperature, of metamorphic grade, and of fluid composition on mass transfer will be evaluated. Quantifying volume changes due to water/rock reaction can be addressed by assuming conservation of mass for one or more immobile components. Another approach is to quantify trace element mobility during basalt alteration. Comparative analyses of trace element concentrations of geothermal fluids and secondary minerals from the production zones in specific drillholes will allow evaluation of the degree to which trace element concentrations of aqueous solutions are controlled by partitioning equilibria with secondary minerals.
(4) model the magma-hydrothermal system including the supercritical regime. Investigation of the dynamics of hydrothermal activity and near-critical behavior will involve establishing the thermal stages of the system from analysis of thermal gradients, micro-seismic and conductivity datasets, distribution functions of fluid inclusions, and curvature of thermal fields. The chronology of fluid percolation paths and the nature of alteration mineral assemblages and mineral zonation patterns will help detect near-critical behavior, and provide input for computation of models of magma-hydrothermal interaction.
Sample Requirements. In view of the very small amount of drill core available from the geothermal systems being considered as targets by the IDDP, it is desirable to obtain as much core as possible. The highest priority is for cores below 2000 meters depth, in or near the supercritical zone, and specifically near zones from which fluid samples are obtained. If the IDDP drills a core hole by re-entering and deepening an existing well it would be desirable to consider collecting side-wall cores in the open interval in that well, or else coring a slim hole alongside it, if costs and technical considerations permit.

Similarly preexisting rock samples and data already available from a borehole that is to be deepened should be retained and curated by the IDDP for study by the project.

Studies During Drilling. Because of the need to recognize supercritical zones in real time, and to anticipate potential hazards during drilling, it will be necessary to operate a petrographic laboratory at the well site equipped with at least fluid inclusion and thin section capabilities. Otherwise sample handling and curation will be patterned on past ICDP projects (for example the Hawaiian Scientific Drilling Project). A formal sample-handling protocol will be implemented. The basic core description should include lithology, alteration, stratigraphy, structural and extrusive/intrusive relations, and pre-drilling fracture distribution, orientation and cross-cutting relations.

Post-drilling Studies. Subsequent petrographic descriptions should start with detailed descriptions of primary mineralogy and textures and secondary or alteration mineralogy and textures. These studies should address alteration and replacement of primary minerals and deposition of secondary minerals in open spaces and within vesicle- or vein-wallrock zones adjacent to healed fractures. Geochemical studies of whole rocks, minor and trace elements and stable and radioactive isotopes will then follow, according to the needs of specific investigators. Samples will be selected for geochronologic and petrophysical characterization including porosity and permeability, electrical resistivity, seismic velocity, natural gamma/neutron density, and magnetic susceptibility and paleomagnetism.

Integration and Interpretation. Most importantly these data will be integrated with regional geologic and geophysical data, paying specific attention to the nature and history of the fracture network and to the relationship of this network to the tectonic and geothermal history of the system on local, regional and global scales. All of these proposed studies are relevant to furthering our understanding of the origin, nature and economic potential of the supercritical zones in Iceland. In terms of global geoscience these studies also relate to issues such as:

(1) the time and spatial relationships in fluid chemistry, alteration minerals, and isotopic systematics during evolution of sub- to super-critical geothermal systems on an ocean-spreading ridge;
(2) the mantle contribution to volatiles in ocean-spreading ridge hydrothermal systems;
(3) and global geochemical cycles that control, for example, ocean chemistry. Another example would be mechanisms for the generation of methane and higher hydrocarbon compounds in water-basalt geothermal systems, with implications to the global methane flux.

REPORT OF THE PANEL ON FLUID STUDIES

The fluid studies panel outlined a program of study that addresses fluid sampling, analysis, and interpretation, and it identified tasks that must be completed before and during drilling. The panel discussed the relative merits of the three areas being considered for drilling and concluded that drilling into supercritical conditions could give valuable results in all of them. However, drilling at Reykjanes would be of more interest to the international scientific community primarily because of the interest in black smokers, ophiolites, and mid-ocean ridge processes.

One of the principal emphases of the fluid sampling program should be to obtain matched fluid and rock samples at fluid production points in the deep reservoir, since the chemistry and thermodynamics of the geothermal system can only be adequately described and interpreted from a knowledge of the total rock-water system. Such paired fluid-rock samples would be among the most valuable scientific products of the drilling. Such samples will optimize the ability to interpret both fluids and minerals, and would open opportunities for novel thermodynamic studies.

Depending on costs, a second desirable goal would be to core the entire length of the drill hole. Among reasons for such coring is the embarrassing lack of information from cores in Icelandic geothermal systems in general, and ability to address specific questions such as why δD in deep fluids at Reykjanes is ca. -20 $^{0}/_{00}$ even though these fluids are apparently modified seawater.

Ideally every fluid-producing horizon should be sampled during drilling, and, ideally, each productive horizon should be cased off or cemented so as to prevent mixing of fluids from distinct aquifers. This would entail suspending drilling for a period to allow thermal recovery and to flush out drilling fluids by the production of fluids from the well. If drilling were to be stopped immediately when total loss of circulation occurs, a roughly representative sample of the fluid could likely be obtained after two or more days of discharge. Unfortunately, such an extensive program of sampling would be time-consuming, expensive, and technically difficult. However the scientific value of the fluid samples is great. A further concern is that repeated thermal cycling would be detrimental to the integrity of the well casing due to thermal stresses and possible damage by corrosion or scaling. Some participants argued that this plan for sampling is contrary to the concept of the “pipe”, that was discussed extensively at Workshop No. 1. This “pipe” is a replaceable liner intended to protect the well casing against corrosion and scaling.

Owing to various problems with discharge samples (e.g. loss of material to scale, indefinite fluid-gas ratio), it would be most beneficial to obtain downhole fluid samples in addition to well head samples. Downhole samples still require well flushing to clear drilling fluids and to recover the aquifer temperature and pressure, so there is no benefit in that respect. Downhole samples can be obtained by mechanical, electronically controlled devices, or by a novel approach using artificial fluid inclusions. High temperature downhole samplers are under development in New Mexico and Canada that might be deployed for this project. Techniques for artificial fluid inclusion sampling, including potential millimeter-scale inclusions, still need to be developed experimentally, partly involving methods under development at Tohoku University.

Preferably, fluids would be analyzed for nearly all elements of the Periodic Table as well as for key anionic species and light stable isotopes (H, B, C, O, N, S etc.). Sampling and analysis of both filtered and unfiltered samples is necessary. Quantification of many trace elements is considered a valuable contribution of the project that sets it apart from previous studies. Large, ultrafiltered samples for the determination of organic constituents may well be of interest to many scientists. The cost of complete fluid analyses would be small compared to the cost of obtaining the samples.

Recovery of hypersaline brines produced by supercritical phase separation would be of great interest internationally. A careful consideration is required of the nature and the likely residence, of such brines in supercritical systems.

Modeling of fluid properties before drilling will be useful. Such modeling should include boiling of fluids to identify potential mineral scale deposition and fluid pH, thereby aiding in site selection and well design. Such modeling will be tested when the "pipe" is later removed to identify scale minerals formed at each set of discharge conditions. A combination of modeling and experimental work based on produced fluids and rock samples would lead to the derivation of the thermodynamic properties of solid solution end members such as manganese and nickel chlorites, which are not available at present. A study of chemical species involved in slow redox reactions, such at the CH_4-CO_2 and the SO_4-H_2S equilibria, would be of great interest. Such a study would probably require rapid analysis of fluids at the wellhead.

Interpretation of fluids and minerals. The interpretation of the fluid chemistry will rely on fluid analyses, measurements of physical parameters, and on minerals identified in rock samples matched to fluids. Concentrations of incompatible components in altered rock, fresh rock and fluid are essential to constrain the origin of the fluid and to gain a quantitative understanding of water-rock reactions and water-rock ratio. Isotopic data on minerals and fluids in combination with theoretical modeling of mineral saturation in reconstructed fluids with comparisons to the actual observed minerals will enable the development of a well constrained model of the fluid and mineral origins.

Summary. Ideally, we would like to sample fluids from every significant fluid inflow point in the well during drilling, then case off or cement those inflows so as not to mix fluids from separate aquifers. In each aquifer, we would like cored rock samples to match to the fluids. In practice, this ambitious sampling program would most likely have to be scaled down, and focused on the zones of greatest interest. All fluids should be analyzed for a very large set of major and trace elements, light stable isotopes and key molecular species. Using such analyses in conjunction with matching whole rock analyses and analyses of individual minerals, and with numerical modeling methods, we expect to be able to reconstruct the physical and chemical evolution of the supercritical geothermal system.

REPORT OF THE PANEL ON RESERVOIR STUDIES

From the point of view of reservoir studies the well itself has the highest scientific value. The well itself will confirm or reject the existence of an economic resource at depth. Temperatures higher than the critical temperature have been measured in wells in Italy, the United States and Japan, confirming the presence of potential high-enthalpy resources at those locations. However, the well Nesjavellir No. 11 seems to be one of the few examples world-wide where a mass flow has been observed at such high temperatures. Two other examples are the San Pompeo No. 2 well in Larderello, Italy, and the Wilson No.1 well near The Geysers, California.

There will be substantial difficulties in obtaining representative values of reservoir properties from the IDDP well. Coring or any type of drilling will most likely cause some fracturing of the rocks and the parameters measured on the core in the laboratory will most likely reflect only approximate *in situ* values. The same situation also can be true for the fluid that may be contaminated or changed by phase separations before sampling.

There are several problems in state of the art reservoir simulation. At present most simulations of fluid behavior in reservoirs assume properties of pure water, while in reality saline solutions or, alternatively, dilute solutions containing high concentrations of dissolved gas are likely to be present. Temperatures and pressures of critical points of these natural fluids, and their densities and viscosities at and near their respective critical points may be significantly different compared to pure water. Also, even in the case of pure water, physical properties exhibit singularities near the critical point, and these circumstances cause difficulties in conventional simulation work. Simulation with relatively coarse grid has been carried out with reasonable results, but simulations with a fine grid close to the critical point become unstable. Present computer codes are not well suited to describe the behavior close to the critical point and better knowledge about the physical properties of the fluid are needed. Some laboratory experiments could improve the situation. On the other hand, the porosity structure of the rocks (porous versus fractured media) would not have much influence on simulation work in the supercritical region as mobility of a very dilute fluid, or the gas phase boiled off from a highly saline brine, is expected to be very high in the supercritical region.

Recommended Pre-drilling Activities. a) Numerical simulation. Carry out a parameter study describing how a supercritical system could be feeding a conventional sub-critical geothermal system. b) Laboratory experiments on the physical properties of the fluid. c) Detailed mapping of earthquake hypocenters in the drilling areas in order to map the minimum depth of the brittle crust. d) Magneto-telluric measurements to locate the top of the critical zone.

Recommended Activities during Drilling. a) A pressure temperature (P/T) memory tool should be attached to the core barrel at all times. During core recovery, a new tool would be attached. The pressure and temperature would be recorded immediately after the return to surface giving a fairly continuous record of the P/T conditions in the well during the core operation. (No extra rig time. Highest priority). b) Another P/T memory tool should be attached to the outside of the drill pipe. This tool would be retrieved when the drill bit is changed. The purpose of this P/T registration is to achieve pressure- and temperature gradients in the well during drilling. (No extra rig time. Medium priority). c) When significant loss of circulation is observed, an injection test should be carried out in order to record the transmissivity of the well. (The rig time required is 6-12 hours. Highest priority.) d) Downhole logging should be carried out every time the bit is changed. Each log should cover the depth interval from the last change of the bit. (Rig time required 6-12 hours. Medium priority.) e) A microseismic and an SP array should be arranged at the drill-site providing a continuous record of these parameters. Recording would start some months or a year before the drilling operation starts and continue for at least one year after the drilling has been completed. (No extra rig time. Medium to high priority.) f) Continuous recording of gases in the flow line. The equipment would record both the concentration and the type of gases coming up with the circulation fluid. (No extra rig time. Highest priority) g) Upgrade numerical simulation during drilling, if required. (No extra rig time. Lowest priority.) h) A detailed mud logging will be carried out. The usual Icelandic procedure can serve as an example. (No extra rig time. Highest priority.) i) A complete logging program, including lithological logs will be carried out for the whole open hole section at the end of drilling. (Rig time required 24-36 hours. Medium priority.) j) Stimulation of the well by massive cooling of the open hole section and/or by placing a packer into the well and pumping water under pressure into the zone below the packer. (About two days of rig time required. Highest priority.) k) Repeat the wire line logging in order to detect any changing in the condition of the formation due to cooling of the well. (Rig time required 24-36 hours. Highest priority.) l) Vertical seismic profiling and walk away seismic profiling should be carried out in the cold well. (Rig time required 24-36 hours.)

Recommended Post drilling activities. a) Temperature and pressure logging during the thermal recovery of the well. The recovery time might be of the order of weeks or even months. Higher frequency of logging is required at the beginning of this time than in the end. These logs give the most reliable information about the location and the nature of the feed zones in the well. (Highest priority.) b) Recording in the seismic and the SP array should continue for about one year after the drilling has been completed. (Medium priority.) c) Down-hole fluid sampling can be done in connection to other logging activities performed at this time. (Lowest priority). d) The panel recommends strongly that “the pipe” (the pilot plant) will be constructed in such way that it can be heated by external source (induction heating?) and provided with sensors to monitor the temperature of “the pipe”. By keeping the pipe at constant temperature above the critical point (say at 400°C), the formation of acid by hydrolysis reactions can be avoided. At the same time, keeping the pressure gradient from the bottom to the top of the pipe as small as possible will minimize the risk of scaling in the pipe.

REPORT OF THE PANEL ON TECHNICAL ISSUES

This panel was concerned with drilling, well completion and sampling. It benefited from the extensive background provided during IDDP Workshop No. 1. Importantly, there do not appear to be any insuperable technical problems with completing either a pilot hole or a hole deep drilled from the surface to satisfy the scientific objectives of the IDDP.

The Workshop No. 1 recommended two different options for drilling and coring to a depth of 5000 m. Rough preliminary cost estimates for completing the Well Design A, the most expensive option, range between approximately US $10 to $15 million, including all the on site and downhole science, testing, and sampling. This well was designed for the collection of continuous core from a depth of 2400 to 5000 m. The well design and cost estimates were based on extensive experience in drilling geothermal wells in Iceland. The heavy casing needed by this option would require a rotary rig that is larger than that presently available in Iceland. Iceland Drilling Ltd. is evaluating a new rig for completing this work, that would have a capacity of 250 tons with a 1000 hp draw works and two 1000 hp pumps.

An overriding concern is the safety of any drilling into or near supercritical conditions. This concern was expressed in a discussion of the casing program as well as cycling the well during flow tests and attempts to acquire fluid samples. A number of options for sampling fluids from the well without flowing were discussed. These options included down-hole sampling devices as well as the growth of artificial fluid inclusions. At the Kakkonda hole in Japan (> 500 ^{o}C), a form of reverse circulation drilling was used to acquire a fluid sample.

Information on new technologies that could be of value for this project was presented. This included concepts of drilling with casing and of expandable casing. Expandable casing can be used to case a well without size reduction. This is accomplished by inserting casing through an existing string and then expanding the casing once it is in place. Similarly, the Sandia National Laboratory of the USA is working on the development of high-temperature tools for the geothermal industry. Some of these prototype tools could probably be made available for use in an IDDP well.

The high projected cost of the IDDP wells is of obvious concern. Additional recommendations from the scientific panels that a well be cored from the surface to TD would increase the drilling cost estimates. An alternative option is to enter an existing well and drill or core to a greater depth. This option could be considered as a “pilot hole” or “well of opportunity” since it would be testing coring and sampling technology in the pressure-temperature zones defined as being of highest scientific interest. The option has a cost advantage since much of the large diameter drilling and casing would already have been installed. The panel listed the wells that would potentially fulfill the role of a “well of opportunity” (Table 1).

The general condition of these wells and the willingness of energy companies to make such a well available to the IDDP needs to be addressed. According to the data listed in Table 1, the most likely candidate wells would be No. 18 at Krafla and NJ-12 at Nesjavellir. The relative merits of these options involve the present condition of the wells, their scientific advantages, and the need for permission by the owners for IDDP to gain access to the wells. Orkustofnun, the National Energy Authority of Iceland, was given the assignment of reviewing the files and making a recommendation to SAGA and to the Principal Investigators.

GENERAL CONSIDERATIONS AND FUTURE PLANS

If Deep Vision’s long term goals of economic energy production and mineral extraction from supercritical geothermal resources are realized, the approach could improve the economics of high-temperature geothermal resources world-wide. This will require a great deal of technology development over the coming decades. However the first step is to drill in search of such supercritical fluids. The feasibility study, being carried out by the Orkustofnun and its subcontractors, appears to be well on track. The wide-ranging discussions at the workshop reassured participants that the IDDP wells can be drilled and sampled, using available technology and that exciting science of world-wide significance will result.

Discussions with representatives of Deep Vision were very productive. They reaffirmed the commitment of the consortium to the IDDP and their willingness to facilitate scientific studies. Meetings with the power companies will take place shortly to present the ideas discussed above and on site selection. Choice of the site for the first deep well will depend partly on business decisions on financing and partly on environmental permitting. However, the long term expectation is that deep wells will be drilled at all three sites by the power companies, and that these wells will be made available for deepening and coring for scientific studies. From a scientific viewpoint all three sites are appealing.

This prospect opens up the opportunity for a comprehensive scientific program investigating the anatomy of a mid-ocean rift zone, by tying together land–based and ocean-based deep borehole studies with complementary geological and geophysical studies. At a meeting of the SAGA group at the conclusion of the Workshop, the following recommendations were made: 1) As a preliminary step we should consider the options of drilling a pilot hole or further drilling using existing holes. 2) Any preliminary work proposed should address the key scientific and technical issues that are important to our future program of deep (> 4km) drilling. 3) Such preliminary work would be a logical step in the development of the overall program.

Table 1 – Wells of opportunity for IDDP drilling in Iceland

FIELD	WELL	DEPTH (m)	TEMP (oC)	CASING	COMMENTS
REYKJANES	11	2247	320	13-3/8” ~800 m 12-1/4” open	Main feed @ 2200 m
	10	2050	320	9-5/8” liner	
TROLLADYNGJA	TR-1	2308	325	13-3/8”” to 750 9-5/8” liner to TD	1000-1600 entries Poor producer
SVARTSENGI	6	1998	240	9 5/8” to 617	No liner
	12	1488	236	13 3/8” to 606	No liner
NESJAVELLIR	13,16,19	1400-2265	325 @ 1500	9-5/8”” to 800 8-1/2” open w/ 7” liner	All producing
	11	2265	>380	9-5/8” <600	gravel pack 1600-TD New casing required
	12	1856	325 @ 1500	9-5/8” to 775m	Not on production Too far from plant
KRAFLA	6	2200	300		Damage @ 1200 m
	18	2215	278	9-5/8” to 674m 8-1/2” open to TD	Poor permeability
	25			9-5/8” to 1100	fish @ 1100 m 2000 m entry pH 2-4 above magma chamber
	26	2200	340		on injection
	23	2000	240	9-5/8 tp 600 8-1/2 open to 2000	
NAMAFJALL	4	1130	270		erupted tephra in 1977 cemented

APPENDIX 1 IDDP - Membership of SAGA :

Stefán **Arnórsson**		University of Iceland
Jón Örn **Bjarnason**		Orkustofnun, Geoscience, Iceland
Guido **Cappetti**		International Geothermal Association, Italy
Wilfred A**. Elders**	PI	University of California, USA
Gudmundur Ó. **Fridleifsson**	PI	Orkustofnun, Geoscience, Iceland
Robert O. **Fournier**		USGS, USA
Valdimar K. **Jónsson**		University of Iceland
Runólfur **Maack**		VGK Engineering, Iceland
Dennis **Nielson**		DOSECC, USA
Gudmundur **Pálmason**		Orkustofnun, Geoscience, Iceland
Seiji **Saito**	PI	Tohoku University, Japan
John **Sass**		USGS, USA
Alister **Skinner**		BGS, Scotland U.K.
Valgardur **Stefánsson**		National Energy Authority, Iceland

APPENDIX 2a (below) **APPENDIX 2b** (p.13) **APPENDIX 3** (p.14)

IDDP / ICDP Workshop 2 **Agenda Overview** **13-15 October 2002**

	IDDP/ICDP WORKSHOP 2				
	13 October 2002	14 October	15 October	16 October	17 October
	Sunday	Monday	Tuesday	Wednesday	Thursday
09:00	Opening / Announcements / Introduction	Geology/Mineralogy	Panels continue	SAGA -	SAGA - PI
	Status of IDDP Feasibility Study			meeting	meeting
	Workshop goals				First draft of
					Report completed
10:30	*Coffee*	*Coffee*	*Coffee*		
	Science Activities during Drilling	Geochemistry	Panel reports drafted		
12:30	*Lunch*	*Lunch*	*Lunch*	*Lunch*	*Lunch*
	Logging and reservoir characterization	Split into Panels	Plenary session	SAGA - PI meeting	PI-meeting &
			Panel reports		Deep Vision & DT
					continues
15:30	*Coffee*	*Coffee*	*Coffee*		
			Science Plan	Report writing	Science Planning
	Reservoir modelling,	Panels continue	and discussion		Organization
	characterization & fluid handling				Priorities
					Funding etc.
18:00	break		Workshop 2 ends		
19:00	*Reception hosted by Orkuveita Reykjavikur*	Dinner	Dinner	Dinner	Dinner
20:00	*Dinner hosted by the Ministry of Industry*				

IDDP / ICDP Workshop 2

Agenda

13-15 October 2002

	Sunday 13.10.2002		Chairman	Minutes
09:00	Opening of IDDP/ICDP-Workshop 2	Vilhjámur Lúðvíksson	Björn Stefánsson	5
09:05	Announcements and Introduction	Guðmundur Ómar Friðleifsson		5
09:10	IDDP feasibility report status - Fluid Handling and Evaluation Group	Albert Albertsson		20
09:30	IDDP feasibility report status - Drilling Technique Group	Sverrir Thórhallsson		20
09:50	IDDP feasibility report status - GeoScience Group - IDDP well sites	Guðmundur Ómar Friðleifsson		20
10:10	What do we want to achive by IDDP/ICDP workshop 2 - Discussion	Wilfred A. Elders		20
10:30	*Coffee 20 min*			*20*
10:50	ICDP - Data Information System (DIS) for IDDP	Ronald Conze	Seiji Saito	20
11:10	IDDP / Geological/mineralogical study (solids)	Hjalti Franzson		15
11:25	IDDP / Geophysical study (physics)	Benedikt Steingrímsson		15
11:40	IDDP / Geochemical study (fluids)	Halldór Ármannson		15
11:55	IDDP / Wellbore imaging and status of stress field	Grímur Björnsson		15
12:10	IDDP / Core logging - HSDP model	Dennis Nielson		20
12:30	*Lunch*			*60*
13:30	Sandia - New high-temperature logging tool development	Randy Norman	Dennis Nielson	15
13:45	Logging operations in high-temperature environments	Gilles Guerin (Itturino-Goldberg)		15
14:00	Deep Drilling into hot basaltic crust with IDDP/ lesson from ODP	Philippe Pezard		15
14:15	Petrophysics and Geothermics	Ernst Huenges		15
14:30	Reservoir Parameter Study	Omar Sigurdsson		15
14:45	Fracture Modelling of Deap Seated Supercritical Geothermal Systems	Toshiyuki Hashida		15
15:00	Deap-Seated, Supercritical Fluid-Rock Interactions in the Icelandic Rift Zone	Noriyoshi Tsuchiya/Greg Bignall		15
15:15	Systematics of magma-hydrothermal processes encountered by IDDP	Denis Norton		15
15:30	*Coffee 20 min*			*20*
15:50	Supercritical Geothermal Reservoir Modelling in support of IDDP	Tom H. Brikowski	Valgarður Stefánsson	15
16:05	Energy Potentials of Supercritical Resources - Model simulation	Sadiq Zarrouck (Watson-Zarrouck)		15
16:20	Multidisciplinary investigation of Tuscany and IDDP high-T reservoirs	Giovanni Gianelli		15
16:35	Seismic experiments to characterize permeability in conjunction to IDDP	James McClain		15
16:50	Paleomagnetic and rock magnetic studies in support of IDDP	Kenneth L.Verosub		15
17:05	Naturally occurring radionuclides in IDDP well fluids and solids	Carter D. Hull		15
17:20	Hydrogen extraction by splitting hydrogen sulphide	Daniel Fraser ((P.Agarwal))		5
17:25	Method of bringing the IDDP fluid to the surface at the Reykjanes	Daniel Fraser		15
18:00	*Break*			
19:00	*Reception hosted by Orkuveita Reykjavikur*			
20:00	*Dinner hosted by the Ministry of Industry*			
	Monday 14.10.2002		Chairman	Minutes
09:00	Characterization of aqueous and silicate melt inclusions (fluid incs. (FI))	Agnes G. Reyes	Mark Reed	15
09:15	Chemical characterization of fluids at wide P-T range (fluid inclusions)	Alan E. Willams		15
09:30	Evolution and source of supercritical fluids in the IDDP well in light of FI	David Norman (Moore-Norman)		15
09:45	Mineral paragenesis of supercritical hydrothermal metamorphism in IDDP	Dennis Bird		15
10:00	Skarn Alteration and Ca budgets in an active IDDP geothermal system	Stefan Nicolescu		15
10:15	Mass transfer attending active metamorphism in IDDP core wells	Peter Schiffman		15
10:30	*Coffee 20 min*			*20*
10:50	Chemical and Isotopic mass balance of sulfur in seawater rech.geot.sys.	Robert Zierenberg	Jón Örn Bjarnason	15
11:05	Assessment of scaling potential from supercritical geothermal fluids	Stefán Arnórsson		15
11:20	Characterization of chem. isotopic compos. of gases in geoth/magmat. trans	Bruce W.Christenson .		15
11:35	Platinum group element geochem. of hydroth. fluids collected from IDDP	Cin-Ty Lee		15
11:50	Trace element mobility under supercritical cond. in Iceland geoth. systems	Everett Shock		15
12:10	IDDP: Proposed studies of high-temperature alteration and fluids	Mark H. Reed		15
12:25	*Lunch*			*90*
14:00	Split into topical panels, e.g.	*Suggestions fo Chairmen/Raporteurs :*		
	(A) Technical Issues	Sverrir Thórhallson / D. Nielson & Valdimar K. Jónsson		
	(B) Fluid studies	Stefán Arnórsson / Mark Reed & H.Ármannson		
	(C) Rock studies	Wilfred Elders / Peter Schiffman & H. Franzson		
	(D) Reservoir Properties	Valgarður Stefánsson / James McClain & Grímur Björnsson		
	Panels continue and may split further			
18:00	*Break*			
19:00	*Dinner*			
	Tuesday 15.10.2002			
09:00	Panels continue			
10:30	*Coffee 20 min*			
	Panel reports drafted			
12:30	*Lunch*			
13:30	Plenary session			
	Reports from the panels			
15:30	*Coffee 30 min*			
	First Draft of Science Plan	Wilfred Elders & Seiji Saito		
	Discussion			
17:00	Announcements and next steps	Gudmundur Omar Fridleifsson		
18:00	Workshop 2 ends			
19:00	Dinner			

IDDP / ICDP Workshop 2 List of Participants 13-15 October 2002

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Iceland Deep Drilling Project

PART II

Drilling Technology

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1 OVERVIEW

The technology and engineering challenges of drilling the proposed IDDP well have been studied. In order to meet the major goals set by the project sponsors a "dual purpose" hole had to be designed – a) to allow fluid to be produced to meet the engineering goals of the power companies and b) to meet the scientific goals by continuously coring the lower part of the hole where the very high temperatures are expected.

As a part of this study a survey was made of the available coring equipment options. One is for small mining-type diameter core, requiring the hole to be reamed later for production, and the other is for a larger diameter core. These coring packages can be accommodated on a conventional drilling rig and both have been used in past scientific drilling projects, but at lower temperatures.

The well casing has to withstand extreme temperatures and pressures and the safety aspects received a special attention in the design process. Two casing programmes of different diameters were evaluated for their costs and benefits. Predictions of fluid circulation temperatures show that the bit can be cooled substantially while drilling a full size hole with a tri-cone bit, but the coring bit receives little cooling due to its low circulation flow rate.

The conclusion of this study is that deep wells can in all likelihood be drilled safely to intersect supercritical temperatures. This would be done by applying existing drilling technology, but with some modifications. It is expected that the drilling will take 258–270 days and the whole project cost be 14.4–15.5 million US$. Several less ambitious alternatives are discussed.

The geological conditions are the great unknowns in terms of temperature, pressure and well stability. Normal rotary drilling to 2500 m has been undertaken in Iceland in a reservoirs of 320°C and in Japan and Italy to 4–5000 m intersecting above supercritical temperatures. Coring with the DOSECC unit proposed here has taken place to 3000 m in Hawaii, but in a relatively cold well. To reach 5000 m and continuously core the section from 2400–5000 m is thus something that has not been done before. Drilling deep scientific drilling in the past has in many cases been reverted to spot coring to overcome slow rates of penetration and well problems. To learn what geological conditions are, is of course, one of the major goals of the IDDP.

2 CONCEPTUAL DESIGN OF THE IDDP WELL

Earlier desk studies for deep drilling in Iceland

The idea of drilling a very deep well in a known high-temperature field in Iceland was born in 1999. The initial idea was to drill a production size hole into supercritical conditions (>374°C) and extract the fluid (brine) for its energy and chemical content. The interest is such high temperatures is in part related to a project proposal to produce magnesium metal from seawater that requires very high pressure steam for drying/dehydration the magnesium chloride intermediate product. Over time the project has evolved into the IDDP project. A report was made by a fellow of the United Nations University Geothermal Training programme (UNU) in 1998 (Huang Hefu 2000) titled "Study on deep geothermal drilling into supercritical zone in Iceland". There the drilling technology is reviewed and a conceptual design made of the well, based on the standard Icelandic high temperature well design. The conclusion was that such a well could be drilled as a normal production hole and should reach a depth of 5000 m and be cased to 3400 m.

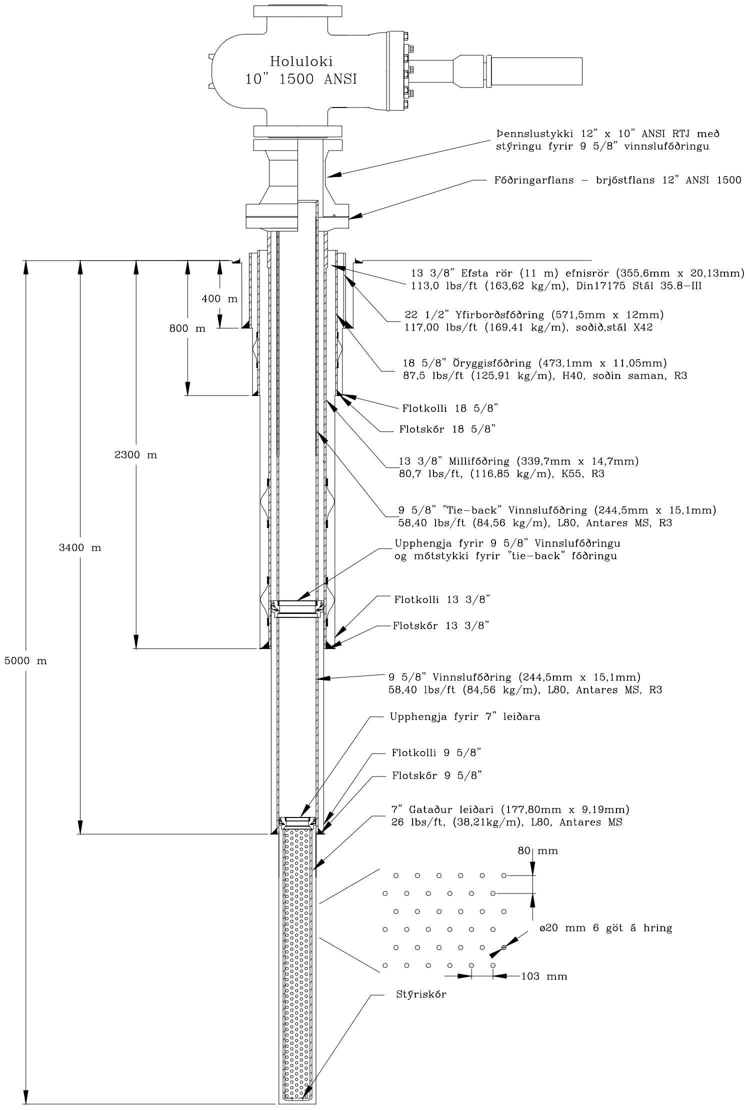


Figure 1. *Well design from 2000 for a 5000 m deep production hole (Huang Hefu).*

Proposal of SAGA 1 report for coring strategies

It was decided early on to open the project for international science and thus the IDDP project was born and support sought from Intercontinental Drilling Project ICDP (Potsdam, Ger.) to organize it. A committee of the IDDP the Science Application Group of Advisors (SAGA) was set up and during their first meeting in Reykjavik June 2001. The implications of the "add-on science" and involving international scientists was discussed. In the SAGA 1 report from that meeting it is recommended that a "dual purpose" hole be drilled to meet the a) engineering objectives and b) the science gaols. For the purpose of fluid production a production size hole is required and for the science objectives obtaining cores is essential. In Figure 1 the alternative coring strategies identified at the meeting are depicted. The recommendation of SAGA was alternative E, namely to core at casing points and continuously core the supercritical zone. Later the well could be opened up by reaming, allowing more fluid to be produced.

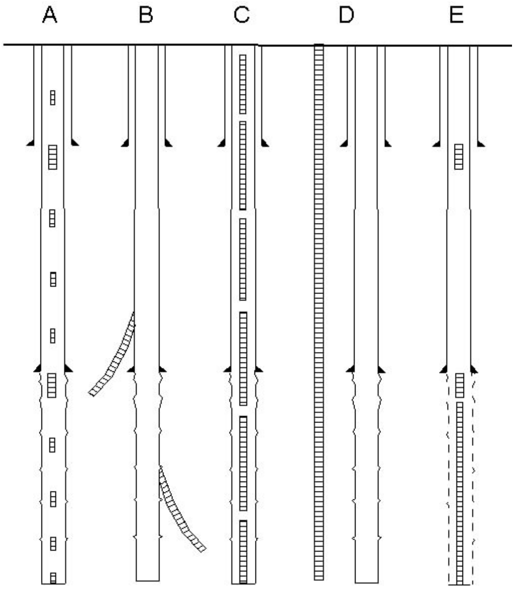


Figure 2. *Coring strategies considered in SAGA 1 report. Alternative E was proposed.*

Proposal of SAGA 2 report after Workshop I

One of the recommendations of SAGA 1 was to organize a workshop (WS I) in March 2001 with financial support from ICDP, mainly to focus on the drilling challenges and discuss what technologies should be applied. Experts with first hand knowledge of the three main scientific coring systems employed to-day gave presentations (Dennis Nielson and Marshall Pardey (US), B. Wunders (Ger.), M. Geldgaf (Rus.)). A follow-up workshop WS II was held in October 2001 to focus on the science. In SAGA 2 report, summarizing the outcome of WS I, it is recommended that the feasibility study should consider the following options listed in Table 1.

Table 1. *Table comparing different coring equipment options (SAGA).*

Four Options	Rig Capacity	Production Casing	Last Hole Dia	Core Size	Hole Size		Cored Sec	**Option**
							km	
Small Diameter Hole	180 ton	7"	6 1/4"	2.4"	3 7/9"	DOSECC	2.3-3.4	**op-1**
							3.4-5.0	
		7 5/8"	6 3/4"	4.0"	6 3/4"	BRR	2.3-3.4	**op-2**
							3.4-5.0	
Large Diameter Hole	250 ton	9 5/8"	8 1/2"	2.6-3.1"	8 1/2"	CCS	2.3-5.0	**op-3**
				2.4"	3 7/9"	DOSECC	2.3-5.0	
				4.0"	6 3/4"	BRR	2.3-5.0	
				2.6-3.1"	8 1/2"	CCS	3.4-5.0	**op-4**
				2.4"	3 7/9"	DOSECC	3.4-5.0	
				4.0"	6 3/4"	BRR	3.4-5.0	

Well designs adopted for the feasibility study

A working group "Drilling Technology" was established to carry out the feasibility study as relates to the drilling of the well. This chapter in the FS reports the results of the working group. In SAGA 2 report, a sketch shows the initial well designs (casing profiles) to be considered, A and B, and coring strategies. The main differences between well A and B is the well diameter. The well diameter influences how suitable the well is for production and also affects the rig selection and well cost. Conventional high-temperature geothermal wells typically require three or four cemented casing strings to be landed in order to fulfill the safety requirements and to isolate unwanted aquifers.

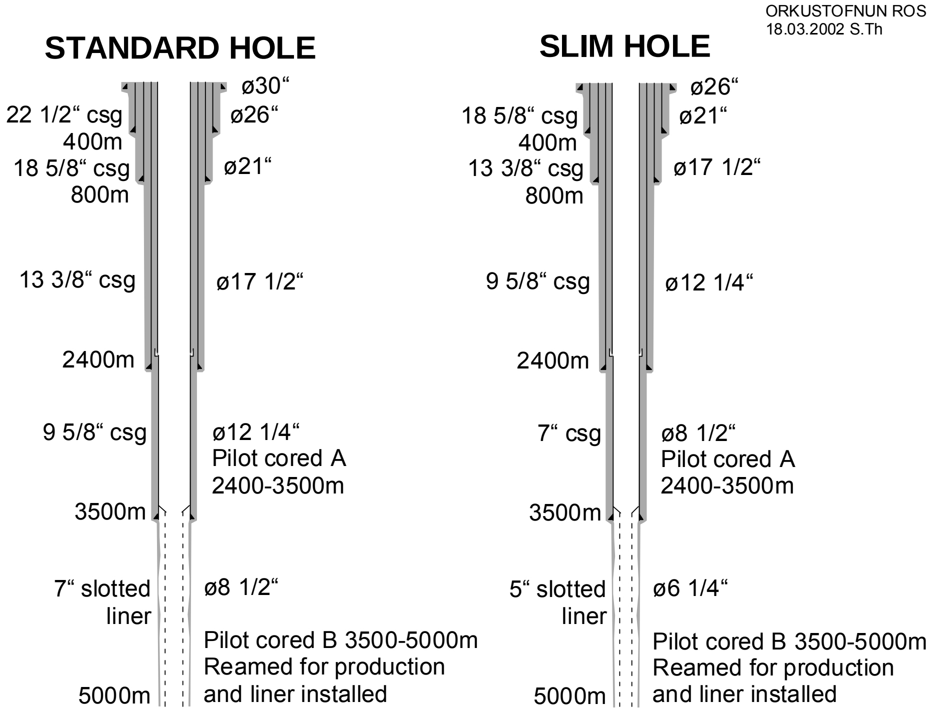


Figure 3. Well designs suggested for the Feasibility Study in SAGA 2 report.

The well designs adopted for the Feasibility Study is slightly different as can be seen from the figure below.

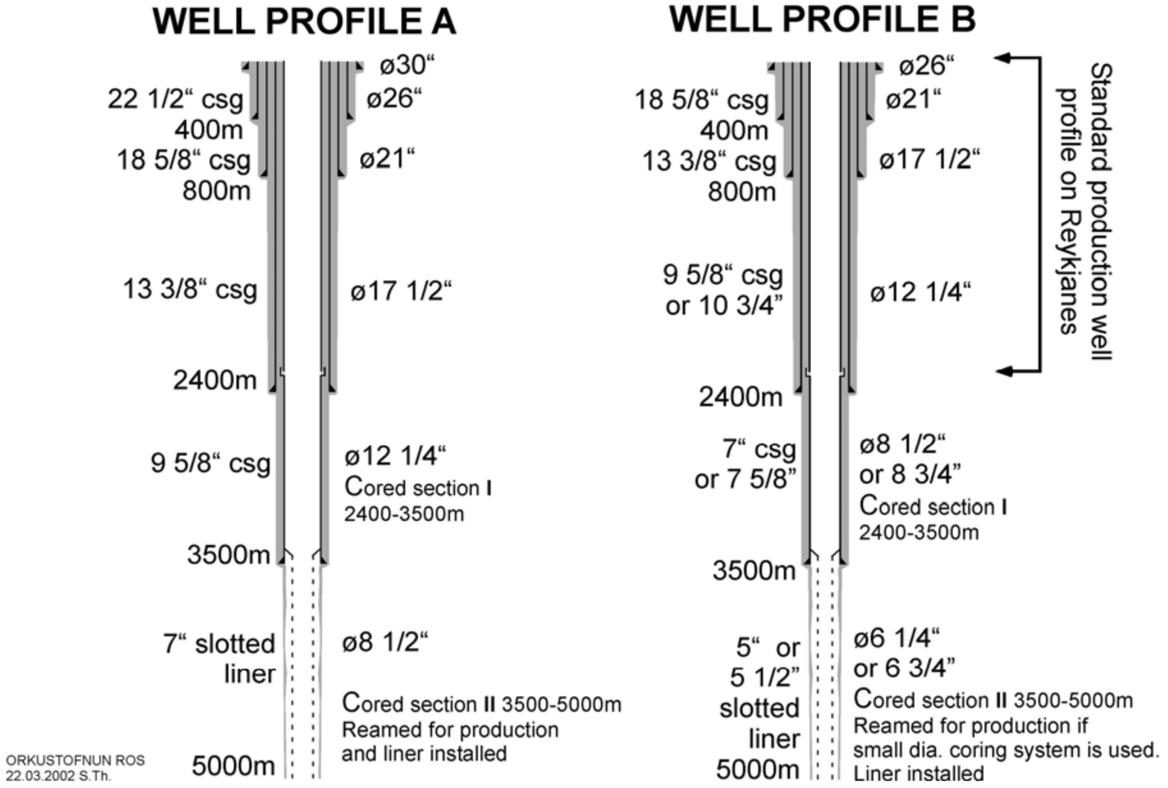


Figure 4. *Well profiles A and B approved by SAGA for the IDDP Feasibility Study.*

3 TEMPERATURE AND PRESSURE

Measured reservoir temperature and pressure at IDDP candidate sites

Drilling into high-temperature geothermal reservoirs started in Iceland in 1947 and since 1960 a total of 120 high temperature wells have been drilled of a size and depth suitable for production. The deepest well drilled up to now is 2500 m in a high-temperature field and 3200 m in a low-temperature field. At present there are six high-temperature fields in production with a cumulative generation of 200 MW of electricity and 500 MW of heat for district heating and industry. The temperatures in these reservoirs typically increase with depth and are as high as they can become in a normally pressured reservoir. The temperature reaches the maximum temperature, that is the boiling point at the respective depth. The temperature increases with depth and follows what is referred to as the “boiling-point depth curve” (BPD). The temperature at the candidate sites for IDDP drilling follow quite closely the BPD curve, as can bee seen in Figure 5. The maximum temperature logged to date in Iceland is 320°C in well RN-10 at Reykjanes. A temperature of 380°C at 2100 m was, however, reported in well NJ-13 at Nesjavellir during a short blowout that was stopped by filling in the well.

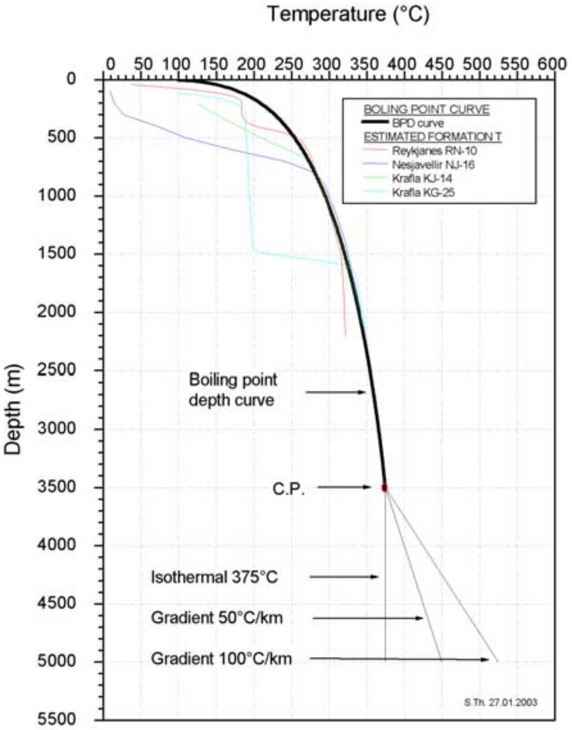


Figure 5. *BPD curve to the critical point and formation temperatures from well logs.*

The water table is commonly at 100–300 m in a stagnant well. The pressure in the stagnant wells increases with depth according to the hydrostatic pressure for the BPD condition and is fixed by the pressure of the most productive feed zone. Actual pressure logs from existing wells at some of the candidate sites are shown in Figure 5. When the well is induced to flow the pressure profile changes due to the pressure drop caused by flow restrictions within the reservoir and also pressure drop in the well. The loss of pressure in the wellbore for the flow up the hole is mainly due to gravity but also due to friction and acceleration of the two-phase flow. Pressure measurements have been made in flowing wells and they are displayed as doted lines.

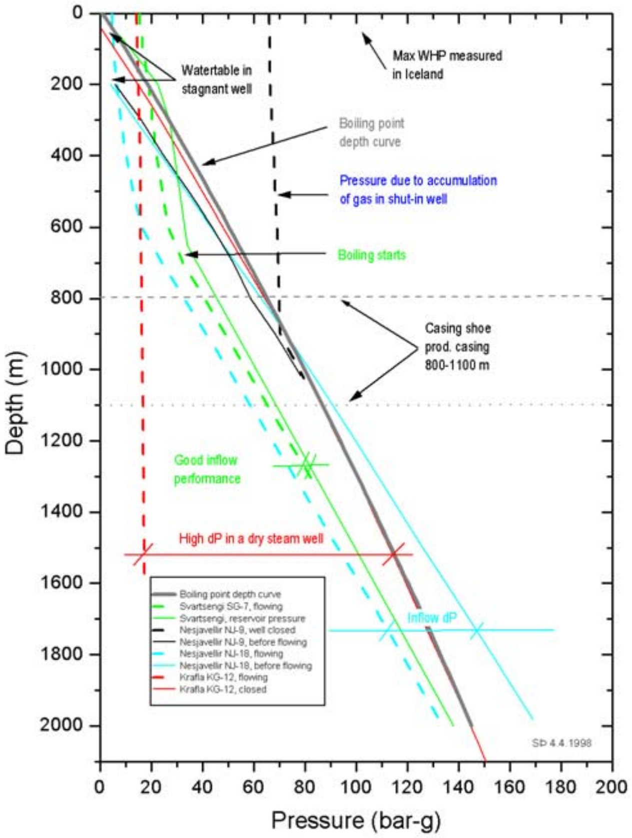


Figure 6. *Pressure logs from existing wells. Static and flowing pressures.*

Reservoir temperature and pressure to 5000 m for well design

To find out what temperature and pressure is like at depth, is one of the main goals of the IDDP. For the purpose of well design and planning two main scenarios were made, numbered 1, 2.

Table 2. *Temperature and pressure assumptions made for IDDP well design.*

- Common for both scenarios is that it is assumed that the temperature will continue to increase with depth and will follow the BPD curve to the critical point (CP) at 375.2°C. This will at the earliest be reached at a depth of about 3400–3500 m. The pressure will also follow the hydrostatic condition to the CP.
- Scenario 1 assumes that at depths below the CP that the temperature will increase steadily. Lacking any firm guidance as to what path the temperature would take, a 100°C/km gradient is assumed.
- Scenario 2 assumes that the temperature below the CP point will be defined by the isochor. An isochor is constant density, in this case constant density with depth.

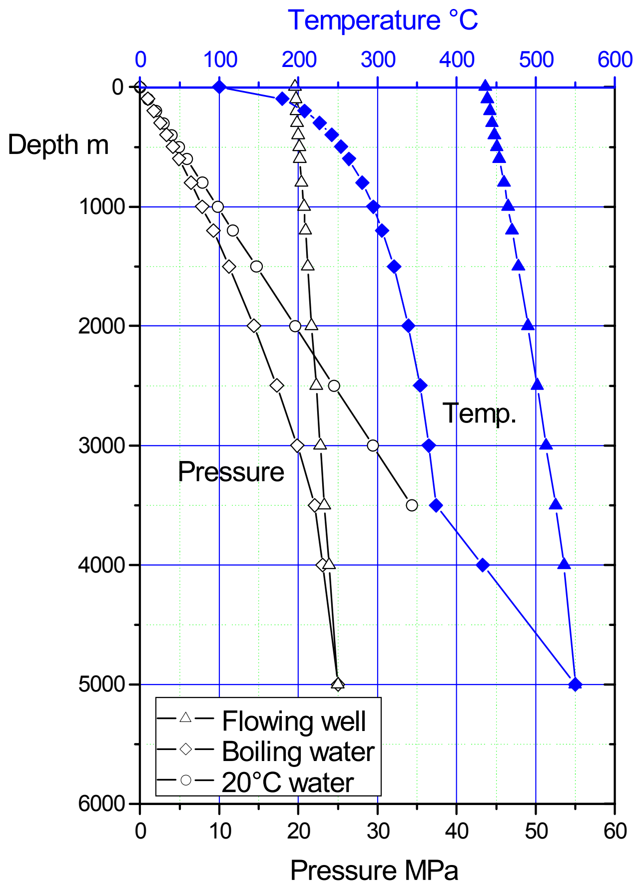


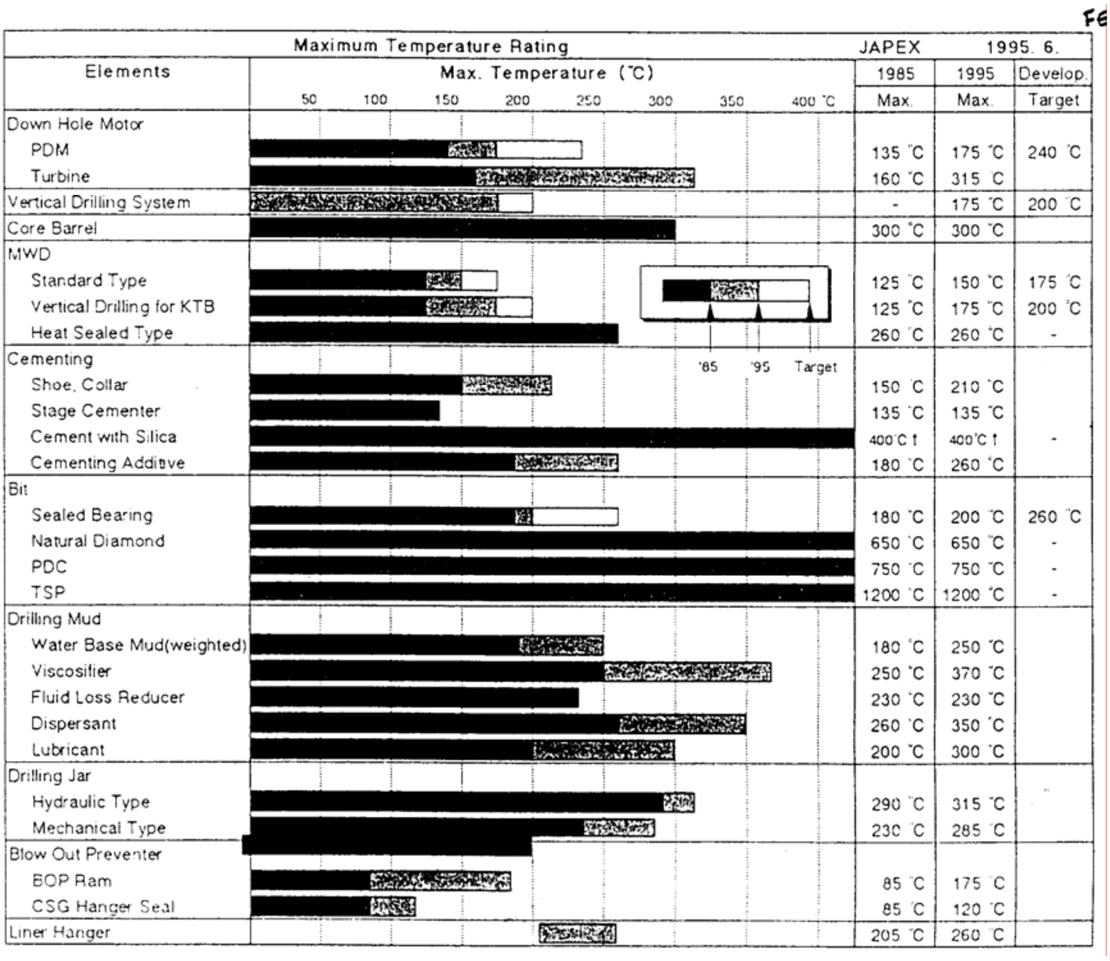
Figure 7. *Scenario 1 for reservoir temperature and pressure–flowing and static.*

As the rock is highly fractured at the candidate sites with recent major faulting and deep fissuring having taken place it was by the drilling working group considered unlikely that the lithological pressures could be reached. Should they, however be reached, it was considered that such a high-temperature reservoir could not be drilled. The well would in such a case have to be plugged and abandoned.

The fact that the IDDP well will reach twice the depth of existing wells and be drilled in such a very high temperature environment for the first time, it is of crucial importance that the investigations on site of the cores and other data be interpreted to give advance warning of conditions that would make further drilling risky.

Circulation temperatures during drilling

One of the functions of the drilling fluid is to cool the bit and well. Information on what the circulation temperature is down hole is important as it influences bit life and dictates what down-hole tools such as: mud motors, drilling jars, logging tools and MWD can be deployed. The following figure shows the maximum temperature rating of drilling equipment and materials at present.



Elements	1985 Max.	1995 Max.	Develop. Target
Down Hole Motor			
PDM	135 ˚C	175 ˚C	240 ˚C
Turbine	160 ˚C	315 ˚C	
Vertical Drilling System	-	175 ˚C	200 ˚C
Core Barrel	300 ˚C	300 ˚C	
MWD			
Standard Type	125 ˚C	150 ˚C	175 ˚C
Vertical Drilling for KTB	125 ˚C	175 ˚C	200 ˚C
Heat Sealed Type	260 ˚C	260 ˚C	-
Cementing			
Shoe, Collar	150 ˚C	210 ˚C	
Stage Cementer	135 ˚C	135 ˚C	
Cement with Silica	400˚C ↑	400˚C ↑	-
Cementing Additive	180 ˚C	260 ˚C	
Bit			
Sealed Bearing	180 ˚C	200 ˚C	260 ˚C
Natural Diamond	650 ˚C	650 ˚C	-
PDC	750 ˚C	750 ˚C	-
TSP	1200 ˚C	1200 ˚C	-
Drilling Mud			
Water Base Mud(weighted)	180 ˚C	250 ˚C	
Viscosifier	250 ˚C	370 ˚C	
Fluid Loss Reducer	230 ˚C	230 ˚C	
Dispersant	260 ˚C	350 ˚C	
Lubricant	200 ˚C	300 ˚C	
Drilling Jar			
Hydraulic Type	290 ˚C	315 ˚C	
Mechanical Type	230 ˚C	285 ˚C	
Blow Out Preventer			
BOP Ram	85 ˚C	175 ˚C	
CSG Hanger Seal	85 ˚C	120 ˚C	
Liner Hanger	205 ˚C	260 ˚C	

Figure 8. *Maximum temperature rating of drilling equipment and materials (JAPEX 1995).*

The most temperature sensitive parts are the elastomers used in O-ring seals of the drill bit, the stator of the mud motors and the electrical components in the logging tools. Too much cooling of the formation rock also may induce special drilling problems, especially for well stability. In conventional geothermal drilling is has been possible to keep the down-hole temperature below 100°C, as long as the mud or water circulation is maintained. For drilling with water the circulation rate is typically 30 l/s for a 8-1/2” bit and 60 l/s for 12-1/4” bit. Actual temperature data has been transmitted from a MWD tool drilling at 2000m in 310°C hot reservoir at Krafla, showing a temperature of only 80°C. For this reason temperature during normal rotary drilling in wells drilled to date poses no special problems for existing commercial tools, contrary to popular opinion.

Several computer models exist that estimate the well temperatures during drilling and warm-up. Some programs also aim at predicting the equilibrium reservoir temperature based on data collected during drilling. To estimate what the circulation temperatures would be for the IDDP wells the STAR program was used. A report describes comparative testing of some of these program and result obtained with the STAR program (Huang Hefu 2000). The cooling depends highly on the rate of circulation (l/s) and whether there are loss zones. The results showed that a conventional well drilled with say 8-1/2” bit and water could be cooled to at least half the bottom hole temperature, whereas a cored hole receives virtually no cooling due to the small circulation rates of 3-5 l/s during such drilling.

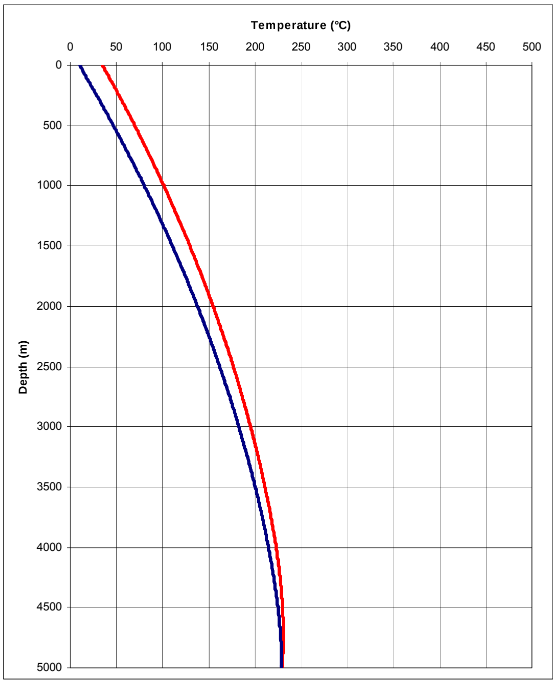


Figure 9. *Mud/water circulation temperature while drilling at 5000 m. Q=35 l/s.*

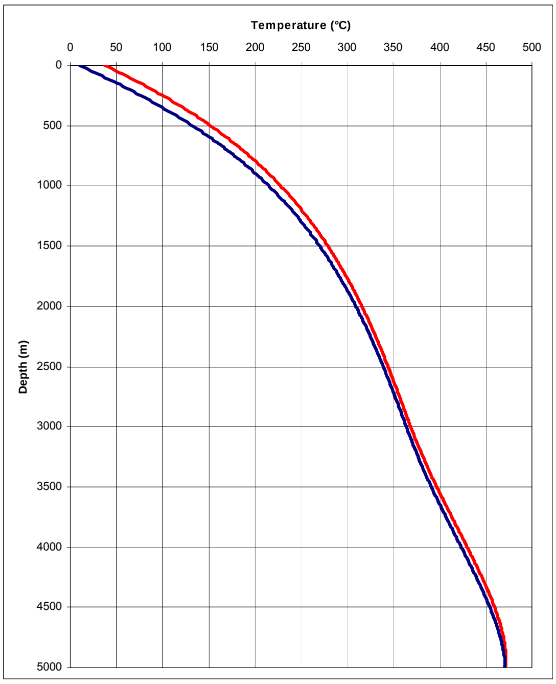


Figure 10. *Mud/water circulation temperature while coring at 5000 m. Q=5 l/s.*

4 GEOLOGICAL CONDITIONS

4.1 Stratigraphy

The general lihology of the drill fields at Reykjanes, Nesjavellir and in Krafla is discussed in part of the feasibility report. The three fields are at different geological setting. Reykjanes is a part of an immature spreading centre astride the Reykjanes Ridge, no intermediate or acid rocks are found and the intrusive rock intensity is relatively low down to 2 km depth (<15 %). No magma chamber has developed as yet. Most likely as similar lithology will be drilled down to 3 km or more, but after that one would expect the intrusive rock intensity to increase. Rock types will be basaltic dykes, both fine grained and doleritic (coarse grained).

The Nesjavellir drill field is within a central volcanic complex, relatively young and immature. Still a magma chamber of some sort has developed at depths, from which acid rocks have evolved and extruded on the surface and in sheeted dikes within the drill field. The intrusive rock intensity below 1500 m ranges between 60–100%. Three types of intrusive rocks have been distinguished, (i) altered fine grained basaltic dykes, (ii) intermediate to acid dykes, which are thicker, and (iii) relatively fresh and young basaltic dykes. One would expect a similar lithology of a dense intrusive complex, possible involving thick dolerite sills or gabbros in addition to the low angle dikes and sheets.

The Krafla drill field is within a mature central volcano, with well established magma cooling chamber at relatively shallow depth, 4–5 km and below. The intrusive rock intensity is 80–100 % below 1500 m in most part of the Krafla field, and involves both gabbros, and coarse grained acid rocks (granophyre) which is much harder than the basaltic gabbros or dolerites. Intrusions of intermediate composition, andesitic, can also be expected, and resemble the acid intrusions in drillability.

Circulation losses can be expect at all depths, but mostly one would expect relatively narrow fractures at intrusive rock contacts within the complex. Most of such fractures have already sealed by mineral precipitates, and will not be detected during drilling. The secondary minerals, except quartz, are softer material than the primary rocks.

4.2 Temperature alteration

Hydrothermal alteration leads to the formation of secondary minerals, formed due to water rock reactions at all temperatures. A pretty regular sequence of secondary mineral is formed upon rise in temperature, a universal relationship. The alteration minerals can be pretty useful in predicting temperatures at each depth during drilling. Still, a care has to be taken on the hydrothermal history, which can be sorted out by drill cutting studies, but much better in drill cores. A simple table is given below, showing the minimum temperature and the temperature range as known. This data is also plotted in Figure 30.

Some minerals are more useful than others in measuring temperatures in fluid inclusions, so call homogenization temperature (T_h). Quartz and calcite are most useful minerals, but epidote, garnets and hedenbergite can also be used, and some others. A fluid inclusion and a petrographic laboratory will be set up at drill site for fluid inclusion studies and mineralogy.

Table 3. *Mineral temperatures.*

Low temperature zeolites (all)	< 100°C
Laumontite (intermediate zeolite)	120-180°C
Wairakite (high-T zeolite)	200-300°C
Prehnite	250°C-350°C
Calcite	20°C - 300°C
Smectite (low-T clay)	20°C - 200°C
Mixed layer clay	200°C - 240°C
Clorite (high-T clay)	240°C -350°C ?
Quartz	200°C upwards
Albite (feldspar)	200°C upwards
Oligoclase (feldspar)	400°C upwards
Adularia (feldspar)	200°C upwards
Epidote	230°C upwards
Wollastonite	260°C upwards
Actinolite (amphibole)	300°C - 400°C
Hornblende (amphibole)	400°C - upwards
Andradite (garnet) ss	300°C - upwards
Other garnets (e.g.gossular) ss	300°C - upwards
Hedebergite (pyroxene) ss	400°C - 600°C
Magnetite	~ 400°C upwards
Andesine (feldspar)	~ 700°C upwards
Quartz – primary mineral	in acid rocks

4.3 Drillability

Reykjanes:	The interval 2–5 km is expected to be similar to the 1–2 km interval.
Nesjavellir:	The interval 2–5 km is similar to what is found in Krafla below 1 km.
Krafla:	The interval 2–5 km is identical to the 1–2 km interval.

4.4 Loss zones

Only fracture permeability is expected. Most loss zones expected to be small due to secondary minerals, but some fracture can be quite open, especially near young subvertical dikes.

The nature of loss zones at depths above 400°C is unknown. The incident in well No.11 at Nesjavellir is the only experience in Iceland. Gas content at high T could be quite high and could mix with the drill fluid and expand upon decrease in P.

4.5 Well stability

One would expect pretty stable rock formations within the intrusive complexes. Intrusive rock margins can be met at all possible angles, which in some cases might affect the drilling performance, possibly lead to key holes etc. A very high thermal difference between very hot rocks and the drilling fluids might lead to well-wall shattering in some rock types more than in others. There are no known case studies of such conditions.

5 WELL CONTROL - SAFETY

Minimum casing depths

The usual criteria for casing depths for drilling of production holes in these three fields is adapted. It assumes a BPD curve and that any upflow of 2 phase fluid (underground blow out) to the casing shoe can be balanced by heavy mud in the worst casa and assuming typical conditions by water only. In all cases a steam filled well will not exceed the overburden pressure at the respective casing shoe depth. Thus the conductor is to 75 m, surface casing to 350 m, intermediate casing to 950 m and production casing to 2400 m (see Figure 11).

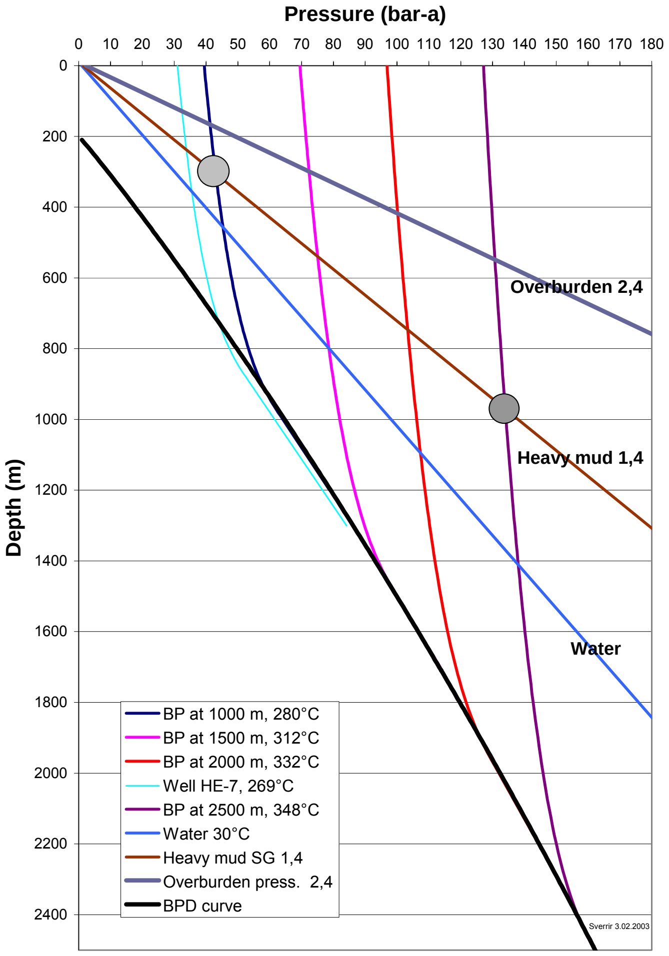


Figure 11. *Pressure profiles expected in flowing wells. Determination of min. csg. depth.*

The minimum casing depth for the drilling to 5000 m is shown in Figure 12. The estimated reservoir pressure is shown by the red line and flowing profiles by the dotted aqua-blue lines. The basic requirement is that it should be possible to pull out of hole with the casing full of water (not to require heavy mud), even with the well flowing from bottom to a vein just below the casing shoe. The upper part of the well may require heavy mud of 1,4 SG to kill an underground blowout. Heavy weight additives (barite–barium sulfate) will thus have to be on location for such an emergency. For this study a depth of the intermediates casing to 2400 m has been adopted. Setting the production casing to 3400 m is thus not a safety issue, rather a question of isolating all fluids at temperatures below the critical point. There is thus some flexibility is deciding on the final cased depth.

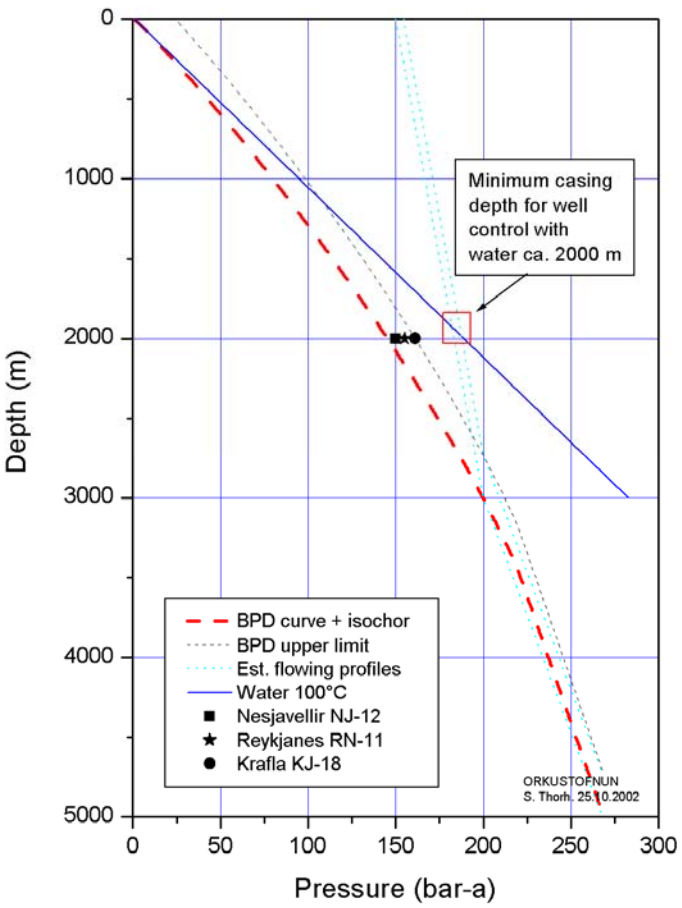


Figure 12. *Pressure profiles for 5000 m well. Actual well pressures at 2000 m also shown.*

Blow out preventer stack (BOP´s)

Geothermal wells are usually under-pressured and thus the wells can be controlled by low density mud or water. A well may kick due to interzonal flow (also referred to as an underground blowout) that can be difficult to control. Kicks due to rapid heating up of the well or due to swabbing are also possible. The main countermeasures is to insure that water is flowing into the well at ALL times, either by normal mud circulation during drilling or by pumping water through the kill line during tripping and logging. In the unlikely case of a blow out the well will be closed and subsequently killed. For this the well will have standard oilfield blowout preventers (BOP) that can close around any object (pipe rams, annular, rotating head) in the hole and also have valves that will close the well totally (blind rams, master valve). At least two valves in series will be able to fulfill the same function so if one fails the other one will work. Conventional BOP´s used in the oil industry are applied to geothermal drilling. They have a pressure rating according to American Petroleum Association (API) or equivalent International Standards Organization (ISO), where e.g. a API valve having a working pressure of 5000 psi is shown as 5M. The working pressure of API 2000, 3000 and 5000 valves as a function of temperature is shown in Figure 14. Drilling the IDDP well to 2400 m, the BOP´s will be rated for 2M and below that depth to 5M. Table 7 shows the expected maximum wellhead pressure and temperature expected the IDDP well for each casing string. The problem with the oilfield BOP´s is the limited life of the elastomer seals at high temperatures. The seals area an essential part of the annular and rotating head BOP´s and important for a pressure tight seal on a ram BOP. Discussions with

major BOP manufactures revealed that all-metal seals are not available and that the longest life of so called “high-temperature” elastomer seals is only 220°C at 200 bar pressure and at these conditions is pressure tight only for a period of a few hours to a few days.
In view of these constraints the way envisioned to control the IDDP well is the following:

Table 4. *Blow-out control procedures for the IDDP well.*

- to close the appropriate BOP valves and introduce cold water immediately into the well below to cool the wellhead. For this there will be a dedicated high pressure pump (HT-400 cement pump) connected to a separate water tank.
- to introduce cold water between the two BOP´s that will be closed. Thus, should the first BOP leak, the second one would be maintained cold enough to hold the seal.
- immediately an effort will be made to KILL the well by pumping large quantities of cold water (or heavy mud) down the annulus and also through the drill string. The depth of each casing string is deep enough to allow the pressure, from the next interval being drilled, to be controlled with water.
- The shear-blind rams allow the drill pipe to be cut and at the same time close the well. By having the tool joint in the proper place the drill string ca be held by the pipe rams, preventing the string to fall to bottom.
- In the unlikely event that these efforts should fail, then the drill pipes can be cut with the shear rams and the drill string allowed to fall to bottom. Then the blind rams will be closed, but as it also has elastomer seals the well will have a master valve that can be closed. The master valve has all-metal seals and can take the full temperature and pressure of the well.
- During all of these operations the option of pumping cement into the hole for a permanent seal is a possibility of last resort.

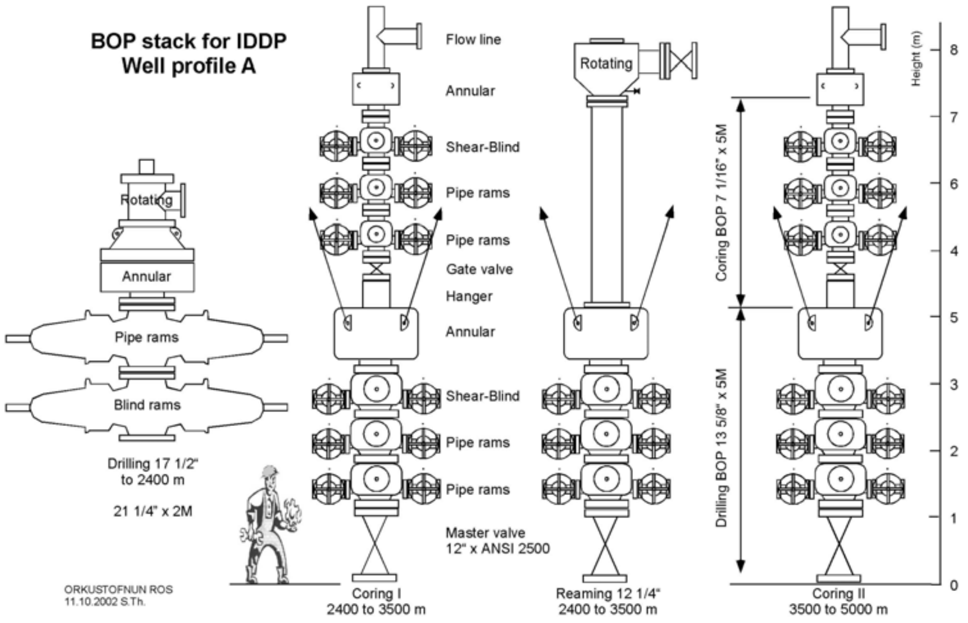


Figure 13. *BOP stack configuration for each phase of drilling the IDDP well, profile A.*

Each BOP will have two side outlets for cooling the BOP and killing the well in case of an emergency. A 3-1/6” ANSI 2500 valve that can take the full temperature will be next to the BOP and a second working valve 3-1/6”x5M remotely operated from the BOP control station.

The rotary drill string will have two float valves with metal back-up seats down by the bit and also the top drive system will have two remotely operated BOP´s in the string below the motor.

The coring unit will have a separate BOP stack above the hanger of the technical casing. The size of the coring BOP is 7-1/16”x5M. A lubricator will go on the top of the coring string before running the wireline to retrieve the core. The lubricator will have a side outlet so that water can be pumped down the coring string in an emergency. The drill string will have a kelly valve 4”x 5M.

Wellhead

The master valve has the function of shutting off the flow under any temperature/pressure conditions that may be encountered at the wellhead. Because of the demanding conditions expected valve manufactures were contacted to assist in the selection and determine availability. The majority of high-temperature wells around the world use a gate valve of the expanding-gate type, now available from several manufacturers.

Valves are classified according to the pressure class and in Figure 14 the rating system of ANSI and API are shown where maximum working pressure is shown as a function of temperature. The expected temperature and pressure for the 5000 m deep IDDP well is shown by a blue box in the Figure 14. From this Figure it becomes clear that the wellhead pressure class of the IDDP well has to be ANSI 2500. The valve has a working pressure of 400 bar at 426°C (6000 psi at 800°F).

Most wellheads in Iceland today are either pressure class ANSI 600 or ANSI 900 but a few ANSI 1500 wellheads are found in Krafla. The body material selection is A217 Gr. WC6 to avoid metal creep. The compressible stem packing is rated to 480°C. The valve can take a thrust of 99650 kg, but the weight of the heavy BOP stack will partly be supported by a special tie-up arrangement. Two side outlets 3-1/8”x5M are on the wellhead for killing the well and pressure measurements. Sizing data for the valves selected is shown in Table 5 and a sectional drawing of the master valve in Figure 15. The delivery time for such a valve is 8 months.

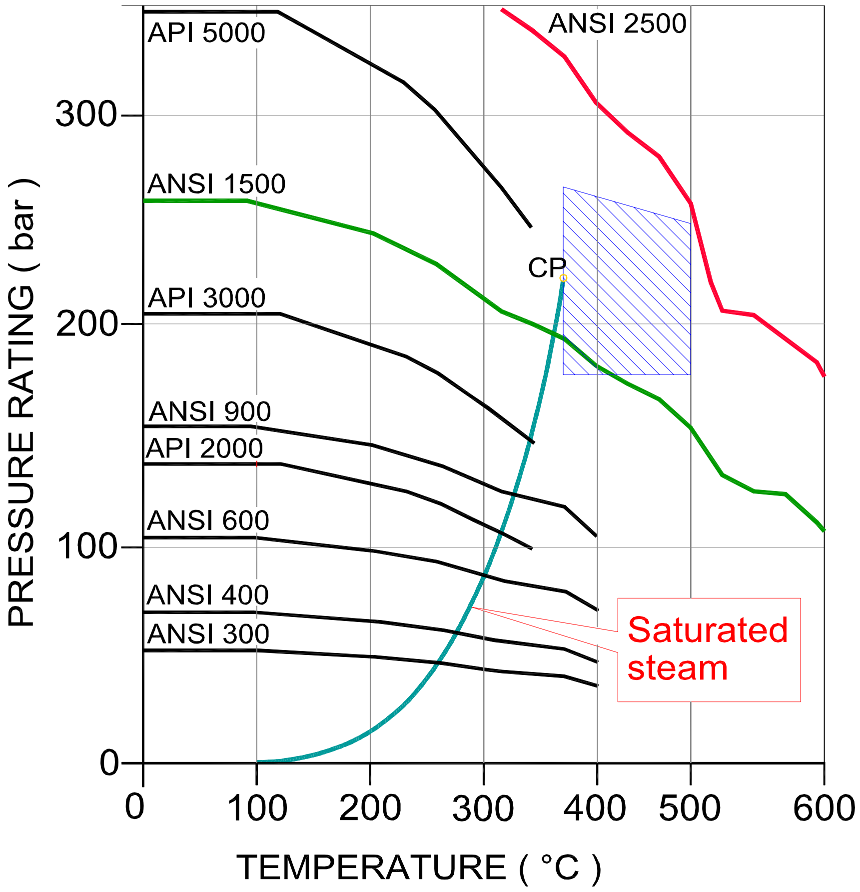
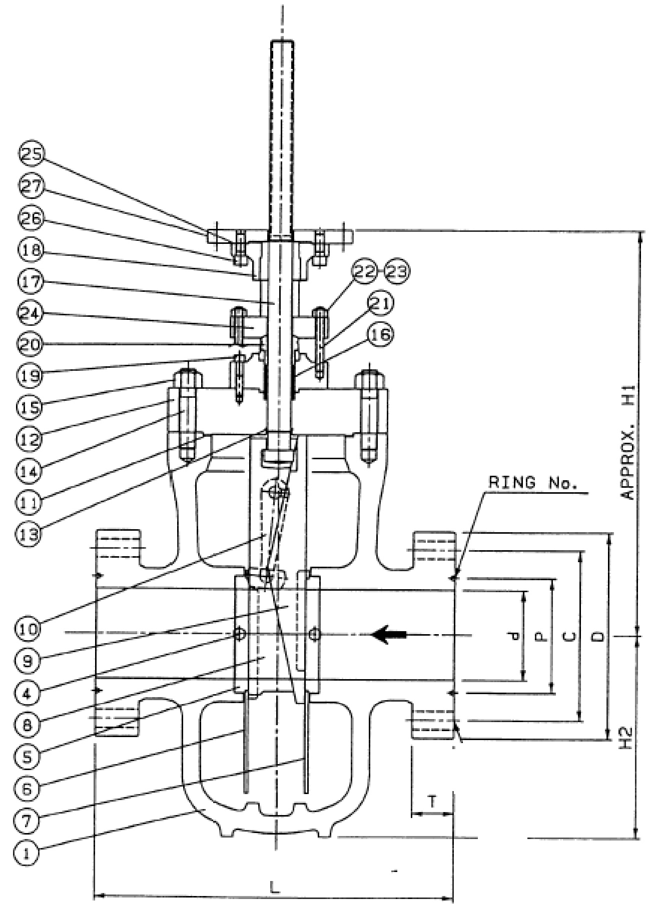


Figure 14. *ANSI and API pressure rating of valves vs. temperature. ANSI 2500 selected.*

Table 5. *Sizing data for IDDP master valve.*

Size	Δ P	Thrust	Torque	Stem Dia	Stem Travel
12"-2500#	250 Bar	99650 kg	403 kg-m	3.1/2" x 0.4" P x 0.4" L	337 mm
10"-2500#	250 Bar	58250 kg	265 kg-m	2.1/4" x 0.333" P x 0.333" L	286 mm
7.1/16" - 5000#	250 Bar	28380 kg	104 kg-m	1.1/2" x 0.2" P x 0.2" L	183 mm
4. 1/16" - 5000#	250 Bar	11300 kg	31.0 kg-m	1.1/4" x 0.2 P x 0.2" L	124 mm
3.1/8" - 5000#	250 Bar	7052 kg	16.2 kg-m	1" x 0.2 P x 0.2" L	102 mm



ITEM	SIZE	d	L	D	C	h	P	T	H1	H2	RING NO.
	10"	254	1000.1	584	482.5	12-51	323.85	119.2	1113	580	R-55
	12"	314.3	1444.6	760	619.3	12-74	406.40	202.0	1520	660	R-60

Figure 15. *Cross sectional drawing of a ANSI 2500 master valve w. expanding gate (TIX).*

6 CASING DESIGN

In the following the casing design is summarised. A more detailed description of the casing design can be found in the appendix.

Design guidelines

For the designing of the casing the following three standards are used:

- API for conventional conditions
- ASME Boiler and Pressure Vessel Code for creep and rupture design
- New Zealand NZS for guidance of conditions

The top part of the anchor casing is designed for creep and rupture conditions and the rest of casing, assumed to be firmly cemented, is designed for conventional conditions such as collapse etc.

Design conditions

The casing design has to withstand extreme temperature and pressure with special attention on safety. It is assumed that the temperature profile will follow saturation conditions for column of boiling water down to the critical point (CP) here assumed to be at 3500 m depth. Below the CP two temperature profiles scenarios are inspected. Firstly it is assumed that the temperature will rise linearly to 550 °C at 5000 m and secondly isochor condition which will render bottom hole temperature of 390 °C. The bottom hole pressure is assumed to be 250 bar and 267 bar respectively.

As a part of a fluid handling and evaluation program after the well has been drilled it is planned to install a temporary pipe in the casing part of the well. This pipe will protect the casing from the supercritical fluid during the fluid evaluation program and if necessary also during production. Therefore corrosion or erosion is not a design condition.

Casing strings

The primary object of the IDDP is to find and access supercritical fluid. Subcritical fluid must therefore be cased off behind cemented casing.

Two casing programmes of different diameters are evaluated:

Table 6. *Casing program.*

	Casing outside diameter	**Casing Depth**
	(“)	**(m)**
Well profile A		
Surface casing	22-1/2	400
Intermediate casing	18-5/8	800
Anchor casing	13-3/8	2400
Production casing	9-5/8	3500
Well profile B		
Surface casing	18-5/8	400
Intermediate casing	16	800
Anchor casing	10-3/4	2400
Production casing	7-5/8	3500

Design loads

The casing design is meant to contain the extreme conditions of a flowing well as well as closed well. The anchor casing and the production casing are the most critical casings. The design loads for these casings are presented in the following table.

Table 7. *Design loads.*

		Anchor casing		**Production casing**	
				Linear temperature profile	Isochor
Casing diameter, Well profile A		13-3/8”		9-5/8”	
Casing diameter, Well profile B			10-3/4”	7-5/8”	
Casing depth	m	2400		3500	
Open hole depth	m	3500		5000	
Open hole					
Highest temperature in open hole	°C	374			

	Saturation pressure at highest temperature	bar	221			
	Assumed highest temperature	°C			550	390
	Assumed highest pressure	bar			250	267
Wellhead						
	Flowing Conditions, 550°C BHT					
	Flowing pressure	bar	195	180		
	Flowing temperature	°C	499	475		
	Flowing Conditions, isochor					
	Flowing pressure	bar	145	142		
	Flowing temperature	°C	340	338		
	Saturated steam column in well					
	Wellhead pressure	bar	177		197	209
	Saturation temperature at wellhead pressure	°C	356		364	369
	Empty well					
	Wellhead pressure	bar	221		250	267
	Ambient temperature	°C	20		20	20

6.1.1 Internal yield pressure

Internal yield pressure is calculated in accordance with paragraph 4.1.1 of API BULLETIN 5C3 and the findings are listed in Table 8 .

Table 8. *Internal yield pressure and well-head shut-in pressure.*

		Well profile A		Well profile B	
Anchor casing	in/lb/ft	13-3/8”/68		10-3/4”/51	7-5/8”/33,7
Production casing	in/lb/ft		9-5/8”/47		
Internal yield pressure	bar	238	326	278	352
Shut-in pressure	bar	221	250/267	221	250/278
Ratio		1,08	1,30/1,22	1,26	1,41/1,27

The internal yield pressure is in all cases higher than well-head shut-in pressure for anchor and production casings.

6.1.2 Collapse pressure

Collapse pressure is calculated in accordance with chapter 2 Collapse Pressure of API BULLETIN 5C3 and are depictured in Figure 16 Collapse resistant as a function of temperature for casing sizes considered for the project. The temperature range is from 20°C to 500°C.

Stage cementing are needed for 18-5/8”, 13-3/8” and 9-5/8” casing for well profile A and 10-3,4” and 7-5/8” casing for well profile B.

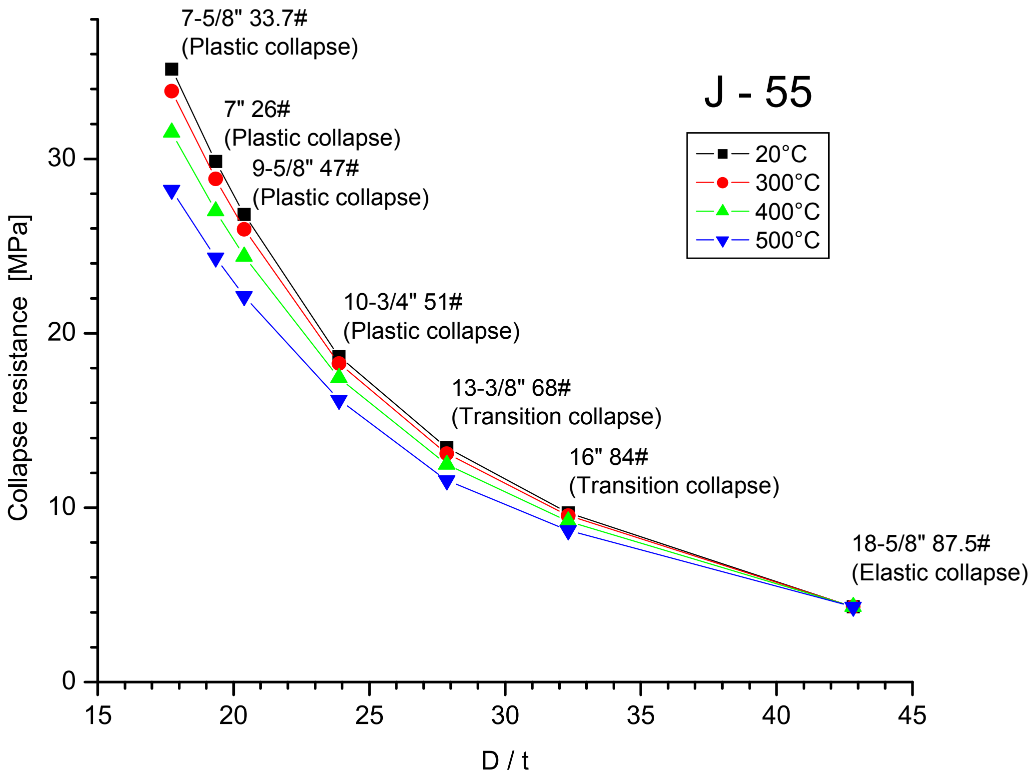


Figure 16. *Collapse resistance of casing vs. Diameter/thickness ratio and effect of temp.*

6.1.3 Heating or cooling strain

Temperature changes of the casing string cause strain (tension or compression) due to hindered thermal expansion of the casing, partially offset by possible state of traction that may have been produced during the hardening of the cemented annulus.

The results for different scenarios are shown in Figure 17 One dimensional strain from hindered axial thermal expansion

The findings are that highest strain is observed when the casing string is cooled from flowing conditions to 20°C.

The effects of plastic yield and of stress relaxation with time should be considered when programming casing settings, well operation procedures and down hole workovers. Initial well heating induces compressive stresses in cemented casing. These stresses tend to decrease with time, at rates which may be significant at high temperature and stress levels, and which vary with the microstructure of the particular casing material. Cooling of the well may then develop higher tensile stresses than occurred when the casing string was installed. (Dench 1970)

Fatigue life of the well will be shorten by repeated thermal cycling and therefore is it essential that thermal cycling should be kept at a minimum.

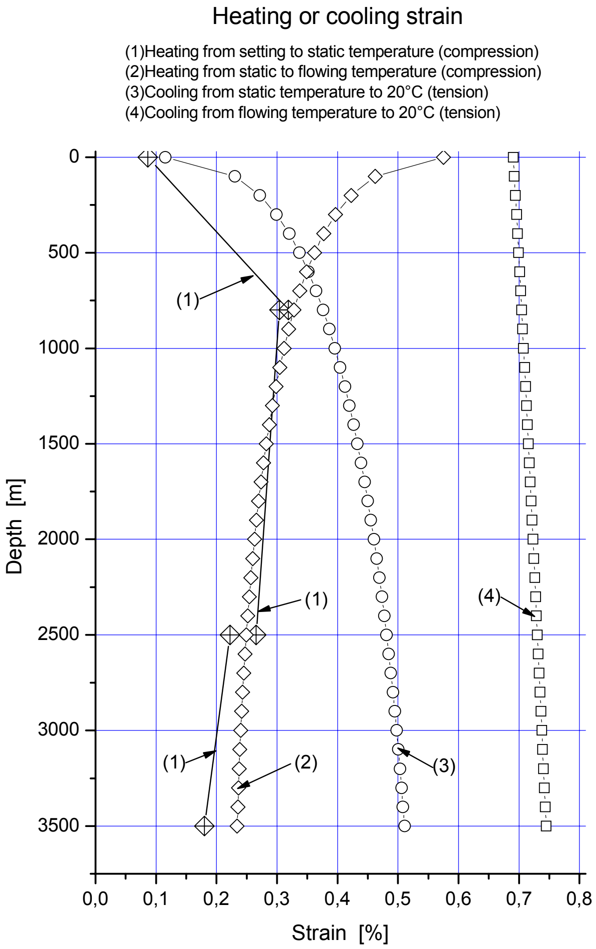


Figure 17. *One- dimensional strain from hindered axial thermal expansion.*

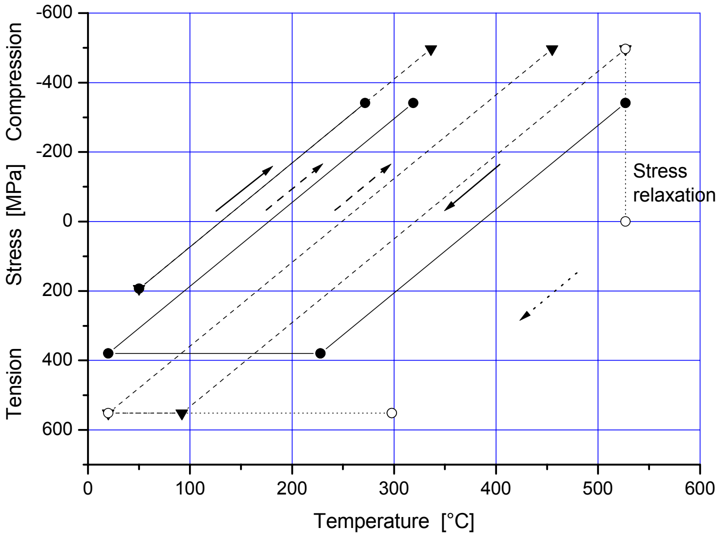


Figure 18. *Axial thermal loading in casing.*

Material selection

Because of the extreme design temperatures attention must be paid to long-time creep when selecting the casing material. It is also clear that because of thermal expansion the cemented casing will yield. The material in the top part of the anchor casing must have good creeping resistance and thus ensure safe operation of the well even for the high temperature and pressure expected at the wellhead. The strength of the material in the cemented casing material should remain intact after yielding, i.e. the larger the difference between the yield strength and the tensile strength the better.

Casing programs

The result of the casing design is summarised in the following:

- For the materials consider for the top part of the anchor casing 2,5Cr-1Mo (SA-213 T22) is consider the best suited material for the time being. The wall thickness of the 13-3/8" anchor casing is 44 mm and for 10-3/4" 31 mm.
- Thick walled grade K-55 casing with premium connections is the best suited for high temperature operation and is planed for the other part of the casing program. Premium connections with metal to metal seals and of higher grade material of quenched and temper steel containing molybdenum is considered to render adequate seal and strength.
- Successful cementing of casings is the basis for safe operation of the well and thermal cycling should be kept to minimum to enhance the lifetime of the well.

The corresponding casing program is presented in the following table:

Table 9. *Casing wall thickness and material.*

	Casing outside diameter	Normal weight of casing	Wall thickness	Casing Depth	Material
	(")	(lb/ft)	(mm)	(m)	(grade)
Well profile A					
Surface casing	22-1/2			400	K-55
Intermediate csg.	18-5/8	87,5	11,05	800	K-55
Anchor csg.	13-3/8	68,0	44,1 / 12,19	2400	2,5Cr-1Mo / K-55
Production casing	9-5/8	47,0	11,99	3500	K-55
Well profile B					
Surface casing	18-5/8	87,5	11,05	400	K-55
Intermediate csg.	16	84,0	12,57	800	K-55
Anchor csg.	10-3/4	51,0	30,4 / 11,43	2400	2,5Cr-1Mo / K-55
Production casing	7-5/8	33,7	10,92	3500	K-55

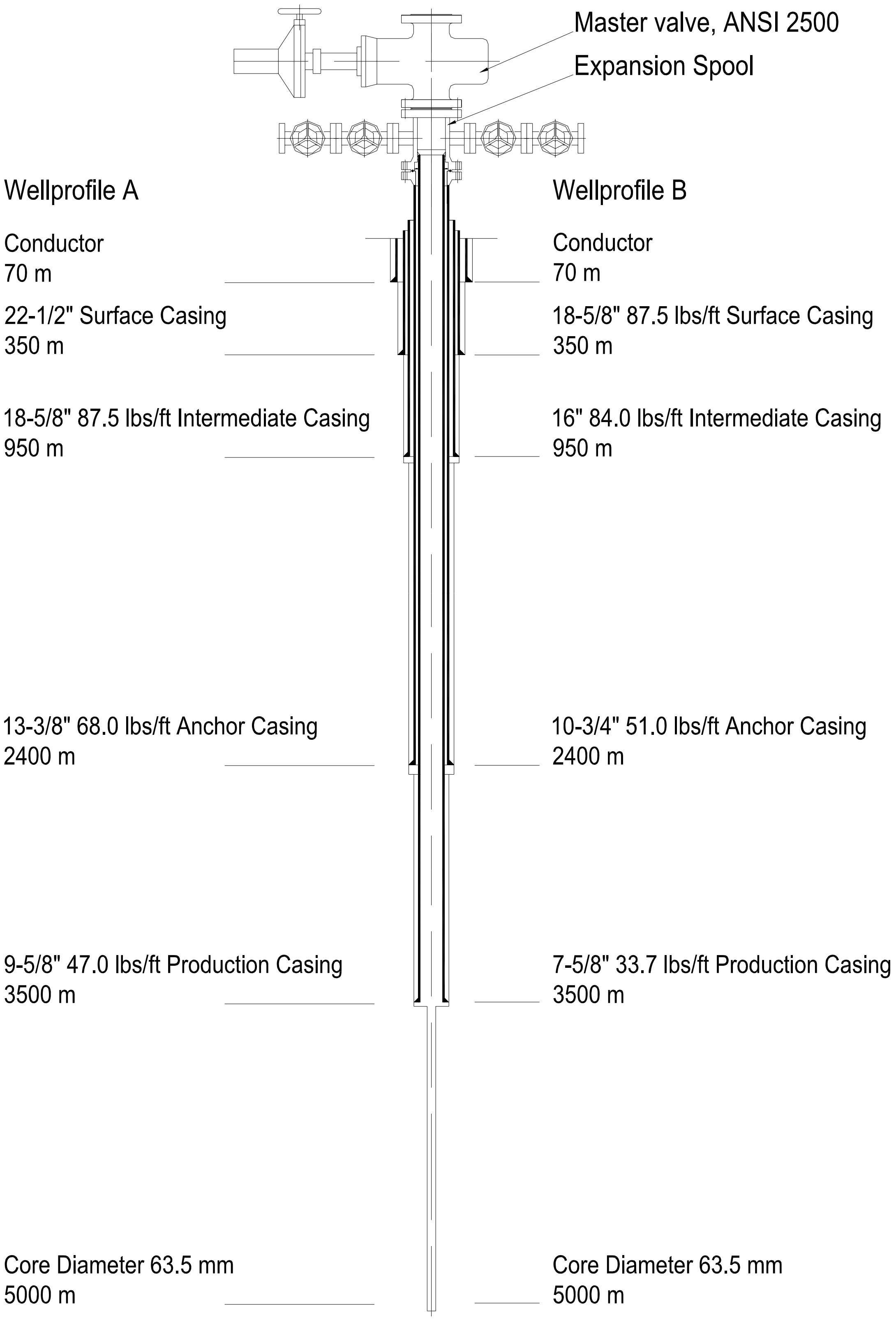


Figure 19. *Casing designs for the IDDP well. Profile A (large dia.well) and B (small dia.).*

Casing connection

Maruyama et al 1990 carried out what appears to be a extensive study of casing couplings for temperature as high as 354°C Their findings are that premium connections with metal-to-metal coupling seals provide excellent seal tightness in thermal wells at temperature up to the maximum testing temperature of 354°C (670°F). Further it was observed that the seal integrity of premium connections can be enhanced by use of coupling that are thicker and/or of higher-grade material than the pin and by using couplings made of quenched-and-tempered steel containing molybdenum. In the same study finds the sealing limits of API BTC to be 200°C (392°C) and API LTC of 300°C (572°F).

Based on this findings premium connections with metal-to-metal coupling seals is foreseen to be used for the project with enhanced coupling of couplings made of quenched-and-tempered steel containing molybdenum.

Alternative well of 4000 m

The anchor casing design conditions for a 4000 m well are, based on the same temperature and pressure gradient below the CP at 3500 m as for 5000 m deep well.

Table 10. *Design loads for 4000 m well.*

		Pressure	Temperature
		(bar)	(°C)
Bottom hole conditions		230	433
At Well-head			
	Flowing Conditions	160	360
	Saturated Steam Column	185	359
	Empty well	230	20

The results of long-time creep calculation are carried out for 9-5/8”, 7-5/8”, 7” and 5” anchor casing at well-head casing. The results as listed in Table 11 Material and wall thickness of anchor casing for well-head conditions.

Table 11. *Material and wall thickness of anchor casing for well-head conditions.*

Nominal outside diameter	Nominal weight	Nominal wall thickness	Material	Calculated wall thickness
(“)	(lb/ft)	(mm)	API	(mm)
9-5/8”	47,0	11,99	K-55	11,9
7-5/8”	33,7	10,92	K-55	9,2
7”	26,0	9,19	K-55	8,6
5	18	9,19	K-55	5,8

The calculations show that K-55 is sufficient for the top part of the anchor casing in a 4000 m deep well.

7 SELECTION OF CORING SYSTEM

Need for coring the IDDP well

It has been stressed by the international scientists that without a core, the scientific significance of the IDDP well would be greatly reduced. It would severely limit their data and to learn as much as possible about to transition to supercritical (2400–3400 m) and the supercritical part of the reservoir (3400–5000 m). The coring will be done in two stages. After stage one is cored the well will be reamed and a new casing cemented before coring the supercritical part. The coring should be continuous. Spot coring at selected depths was not considered appropriate by SAGA as it would not provide enough geological information. For this reason the project is based on continuous wireline coring from 2400 m to total depth. In spite of the strong case presented for coring the plans presented here also consider how to reach the target depth should progress be too slow or other problems appear that would best be solved by switching over to conventional rotary drilling.

Overview of available coring systems

In papers delivered during Workshop I, information was presented on the main scientific coring systems available for deep drilling. They can be divided into four main categories.

Table 12. *Main types of coring equipment (Bernd Wundes).*

A. Coring with conventional systems (API)
B. Coring with API equipment plus small diameter wireline elements
C. Coring with deep drilling wireline systems of special construction
D. Coring with small diameter systems with hybrid applications

A table prepared by Bernd Wundes of Bohrgesellschaft Rhein-Ruhr and shown at the meeting, slightly modified by SAGA after WS I, summarizes the main technical features of each of the three coring systems presented. These coring systems have their main application in geotechnical, scientific and mining industry. They fall into categories C and D listed above and differ in the diameter of hole drilled and also slightly in diameter of the retrieved core.

Table 13. *Technical data for deep wireline coring systems (Bernd Wundes).*

CCS Aquatic	ICDP-WL (Micon)	SK5 BRR	DOSECC			
			Top Str as WLDP	**Cr Brl** and WLDP		
9 5/8"	7"	7 5/8"	5"x7.53 mm			Last Casing
222 mm	155.6 mm	171.5 mm	96 mm			Hole Diameter
80 mm	94 mm	101.6 mm	63.5 mm			Core Diameter
ADP	Special	Special	Hydril	HMCQ		Drillpipe Type
164-168	139,7	139,7	88,9	88,9		Pipe OD mm
197	146	162	99,06	88,9		Tooljoint O D,mm
146	123,5	123,7	74,73	77,8		Pipe ID,mm
144	110	123,5	76	77,8		Tooljoint ID,mm
>3.3	>3.0	>3.1	0,93	0,42		Traction Tensile,MN
30.000	21.000	25.000	4.339	2.000		Makeup Torque, Nm
700-1500	175	250	100	100		Mudflow rate, l/min
0.75-1.5	0,79	0,54				Mud Velocity, Pipe OD,m/s
1.9-3.1	1,29	1,68				Mud Velocity, t-joint OD, m/s
23,5	29	30				Weight in air, kg/m
9000	6358	6358				Depth rating, m for SF=2
Aluminum	G105	P110	L80	SAE4130		Material Grade pipe
	30CrNiMo8V	SAE4145 Hmod	Thread cut in wall			

The drilling rig for all of these coring systems is a basic oil-field rig modified to accept the special drillstring. A top drive system with high speed is required and also precise feed control to maintain proper weight on bit (WOB). Each of these systems have certain beneficial features in terms of the size of the final hole, which determines what testing and logging can take place, the likelihood of reaching total depth and the amount of well cooling. Based on consensus in the SAGA group the DOSECC unit from the United States and the BRR unit from Germany were considered the most appropriate technology. In view of the information available, the fact that this is vertical hole (not deviated) and the desire to use equipment with proven record, it was decided to base the cost estimate in this feasibility report on the DOSECC unit. That unit is described in some detail in the following chapter, based on information from Dennis Nielson the President of DOSECC and Marshall Pardey, of QD Tech, Inc. in Salt Lake City, Utah.

Small diameter hybrid coring system

A university consortium in the United States has developed a novel coring system for deep drilling, based on mining type core barrel. On their home page www.dosecc.org the consortium is described as “DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust) is a nonprofit corporation whose mission is to provide leadership and technical support in subsurface sampling and monitoring technology for addressing topics of scientific and societal importance. Fifty research organizations are members of DOSECC. Our offices are located in Salt Lake City, Utah.”. The coring system is called the DOSECC Hybrid Coring System (DHCS). The basic idea is to install a coring unit in the mast of a conventional rotary rig. This to allows the well to be opened up, cased and cemented as may be required, by removing the coring unit from the mast or setting aside inside the mast. The system uses a mining type diamond wireline core barrel size HQ. The unit consists of a top drive and a hydraulic cylinder for precise feed control, has its own wireline winch and mud pumps and a power pack to run all the equipment (see Table). The rotary drilling rig equipment is thus not in use at the same time, except to hold the hydraulic cylinder and to for tripping the rods. The coring unit is operated from the drillers station in a cabin that houses also the coring instrumentation panels and the computer panels. The cabin is either located on the rig floor or rests on containers beside the mast. The container can be the tool shed/repair shop. The drill rods are stronger than for normal diamond drilling (see Table 15). The drilling fluid is a water based polymer mud and the circulation rate is about 5 l/s. The blow out prevention equipment that comes with the rig is a Kelly valve and a BOP. Two diamond drillers work in 2x12 hrs shifts and the regular rig crew assists them. This unit has a depth rating of 6000 m and been used on several scientific coring projects down to 3000 m and at temperatures to 340°C. The drilling rate, meters per day, is shown for a well in Hawaii HSDP in Figure 23. For the IDDP cost estimate a penetration rate of 25 m/day is assumed to 3500 m and 20 m/day below that depth. Three drillers come with the rig and all of the equipment is transported in three 20 foot and one 40 foot shipping containers.

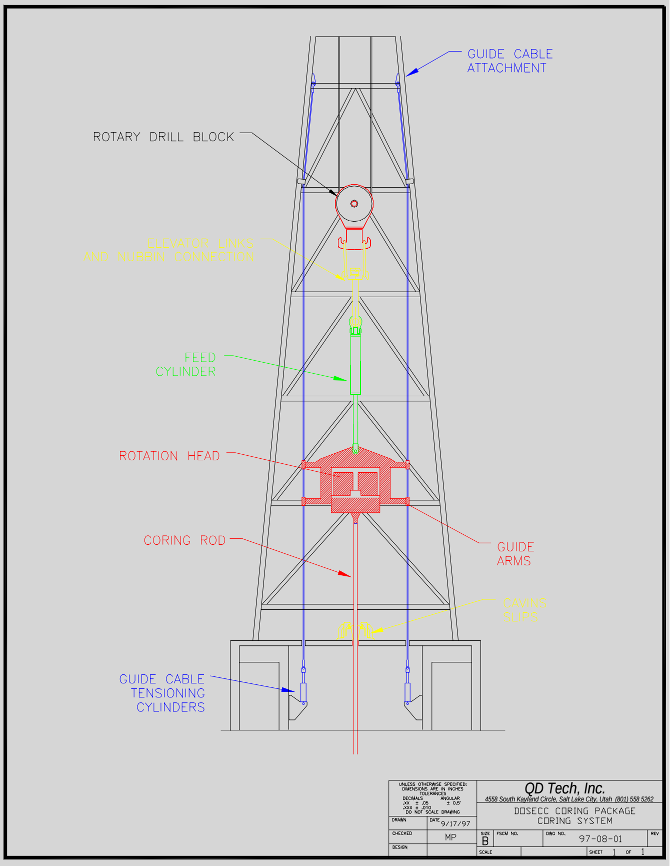


Figure 20. *The feed cylinder and rotation head installed in a mast (DOSECC).*

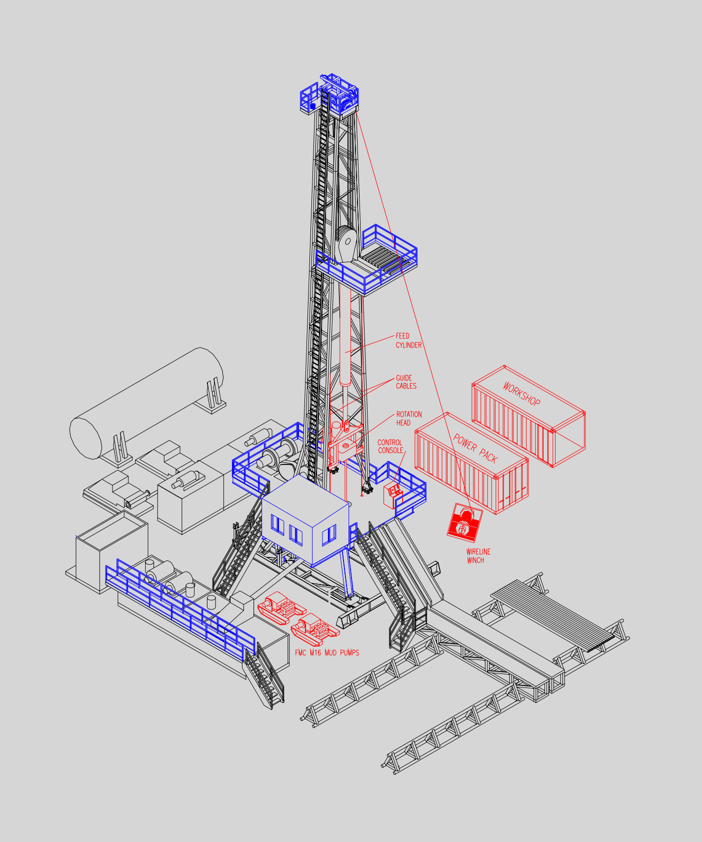


Figure 21. *The DOSECC coring unit fitted to a conventional rig (DOSECC).*

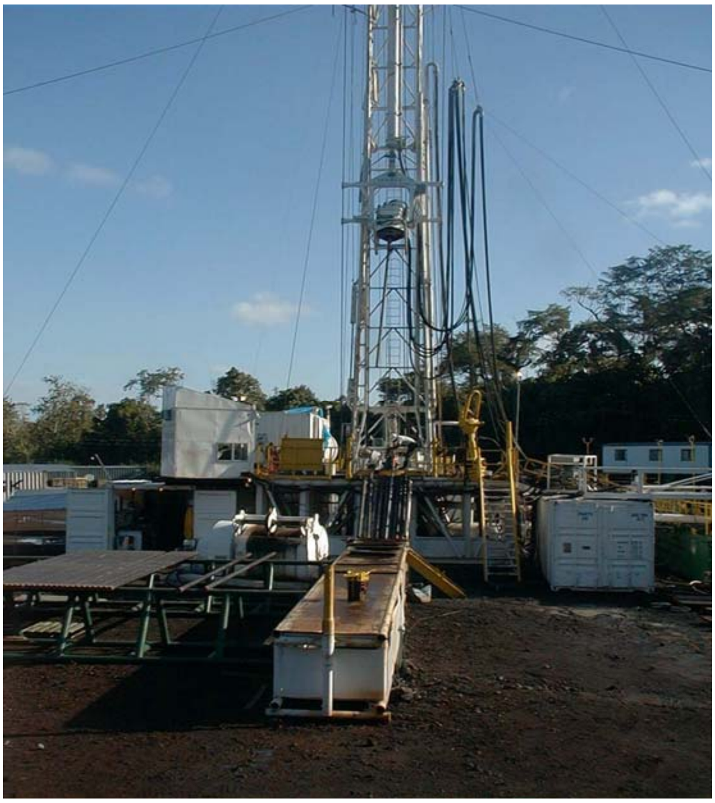


Figure 22. *Photograph of the DOSECC coring unit in Hawaii (DOSECC).*

Table 14. *Hybrid Coring System (DHCS) Rig Data (DOSECC).*

Engines:	1 - Detroit Series 60 - 450 HP Model # 6064-GK33 DDEC Computer Controlled Electronic Engine Management System 24 VDC Electrical Air Compressor
Pumps:	2 - FMC Triplex Plunger Pump Model #M1620 Hydraulically Driven 90 GPM @ 350 RPM 1990 PSI Max. 1 – FMC Triplex Piston Pump Model # L1122B Hydraulically Driven 40 GPM 1000 PSI Max.
Rotary Drive:	Hydraulic Top Drive 185,000 lb. Dynamic Capacity 250,000 lb. Static 0 – 900 RPM Variable Torque 4” IF Pin Down Floating Spindle King 2.5 BL Swivel Kelly Valve 5000 psi 4” IF Pin Down 4 – 1.125” Dia. Guide Cable Arms
Feed Cylinder:	25’ Stroke 12” Bore 5.5” Rod Cylinder 250,000 lb. Capacity Elevator Upper Connection 3 ½” D.P. Square Shoulder Load Cell Lower Connection to Top Drive Frame
Wireline Winch:	Hydraulically Driven Capacity 20,000 feet of 0.472” Cable 323 Feet/Min. Bare Drum 440 Feet/ Min. Full Drum 20, 454 lb. Pull Bare Drum 15,244 lb. Pull Full Drum c/w Hydraulic Failsafe Brake Manual Band Brake
Power Pack:	Container Enclosed Skid Mount 500 Gallon Reservoir Dual Air/ Oil Coolers High Pressure / Return 5 Micron Filtration
Control Console:	Electronic Control for all Coring Functions Skid Mounted for Rig Floor Placement
Instrumentation:	Wireline Counter, Rate and Weight Indicator String/Bit Weight Rotation RPM Pump GPM (2) Hydraulic Feed Pressure, Mud Pump Pressure Drill Head Position / Feed Rate Digital Display and Recording
Accessories:	Cavins Model “C” Air Slips Dressed for 3 ½” & 5” Rods Eckels 4 ½ Hydrauic Tubing Tongs
Mud Mixing and Cementing Unit:	2 – 1200 Gallon Vertical Hoppers 2 – Hydraulic Harrisburg 1 7/8” Centrifugal Mix/Transfer Pumps 2- Jets Mixers and Work Deck
Support Equipment:	Shop Container c/w Hydraulic Hose Crimper Hand & Power Tools Lighting and Power Distribution Drill Press & Bench Grinder Storage Shelving Torch Set Bolts, Nuts and Misc. Spares Parts Container c/w Lighting Storage Shelving

Table 15. *Proposed DOSECC tapered drill string to core to 5000 m. Safety factor 2.6.*

Depth Range, m	**Rod**	**wt, kg/m**	**OD, "**	**OD, mm**	**String Weight,kg**
0-1,600	Hydril S125	12,2	3,868	98,3	19.520
1,600-2,800	Hydril N80	12,2	3,868	98,3	14.640
2,800-3,800	HQRHP	11,5	3,5	88,9	11.500
3,800-5,000	HMCQ	8,5	3,5	88,9	10.200
				TOTAL	55.860
				Wt/m	11.17 kg/m

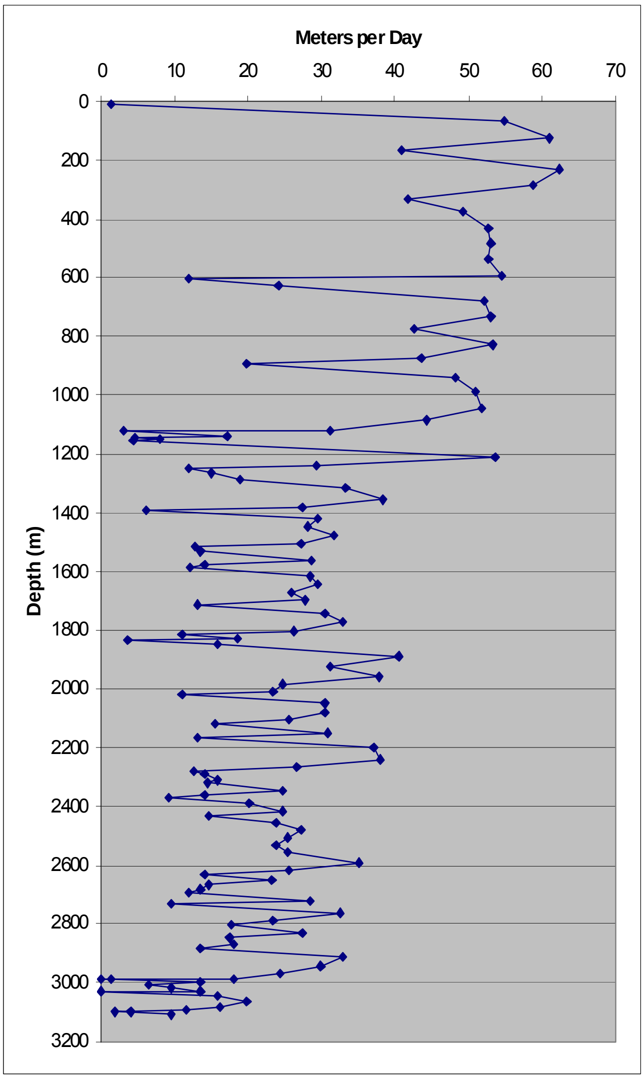


Figure 23. *Rate of penetration vs. depth for the HSDP phase 1 (DOSECC).*

Core barrels

The DOSECC unit uses a HMCQ core barrel. The hole diameter is 98 mm (3.850") and the core is 61 mm (2.400"). The inner tube can be made up in lengths to 30 ft. Impregnated diamond bits are used.

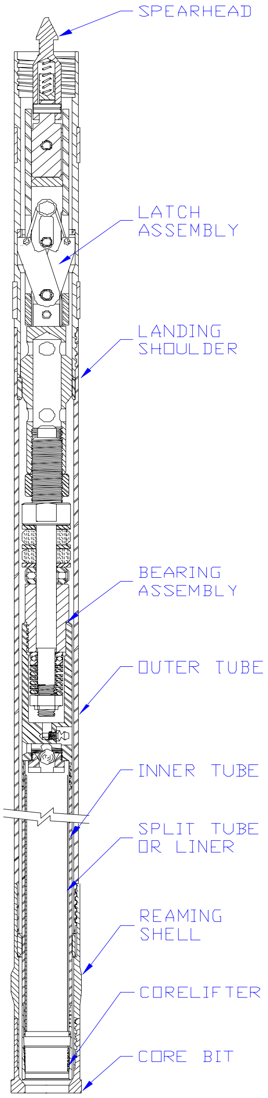


Figure 24. *HMCQ small diameter core barrel used with the DOSECC unit (DOSECC).*

Should progress be too slow or other problems arise while coring, it may be necessary to switch over to conventional drilling of a full size hole and spot coring. Then a conventional API oil-field core barrel (not wireline) would be used that can take a core of 100 mm diameter in a 215,9 mm (8-1/2”) hole, see Figure 25.

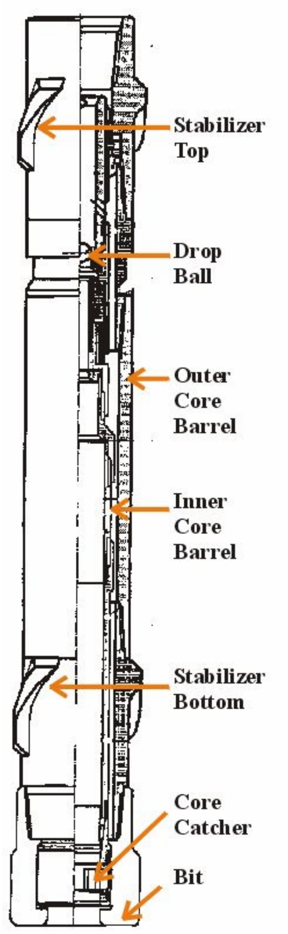


Figure 25. *Large diameter API core barrel for spot coring. Has cored at 280°C in Iceland.*

8 DRILLING PROGRAMME

Conventional drilling to 2400 m

Over 100 high-temperature wells have been drilled in Iceland. In the fields being considered for IDDP drilling the following drilling has taken place.

Table 16. *Wells drilled to date at potential IDDP sites.*

Field name	Number drilled	Max. depth (m)	Max temp. (°C)	Max. dia (“)
Krafla	34	2200	350	9-5/8”
Nesjavellir	22	2265	380	9-5/8”
Reykjanes	12	2500	225	12-1/4”

Drilling the well down to the point where coring will begin at about 2400 m has thus been done before. Actual drilling progress curves are shown in the Figure 26 for two wells recently drilled on Reykjanes peninsula. It shows trouble free drilling with e.g. no stops for cementing except at casing points. One well was drilled in 42 days with a mud motor to 2500 m, including 5 days spent waiting for casing shipment. The other well was drilled with conventional rotary drilling to 2300 m in 65 days. Drilling and casing of the IDDP well with a 12-1/4” bit to 2400 m is estimated to take 55 days.

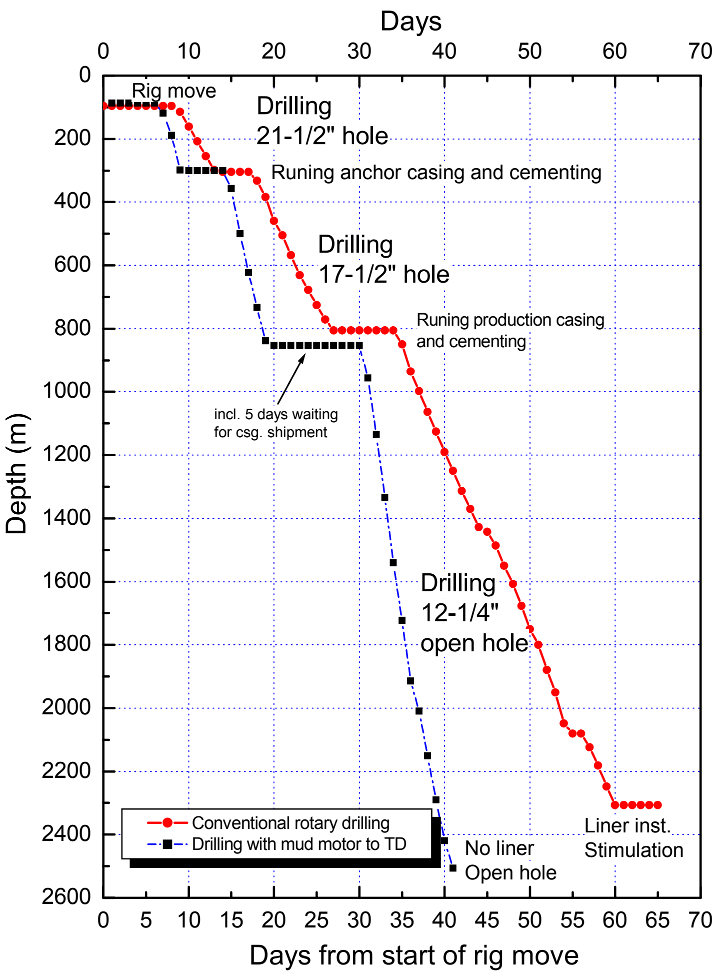


Figure 26. *Actual drilling progress curves for recently drilled wells w. 12-1/4" to TD.*

Only wells on Reykjanes peninsula have been drilled with 12-1/4" bit to total depth. In Krafla and Nesjavellir the wells have a diameter of 8-1/2". The diameter to that depth of the two IDDP wells of type A and B is 17-1/2" and 12-1/4" respectively. Drilling the large diameter program will thus require a bigger rig (see next chapter) and will be outside the envelope of experience in Iceland. The sequence of drilling the IDDP well is the following:

CONDUCTOR

- The well is first pre-drilled with a truck mounted rig to 70 m and a conductor casing installed and cemented.

SURFACE CASING

- The cellar and drill site is prepared for the large rig.
- Rig-up and install BOP´s for drilling to 350 m. Test BOP´s.
- Drill the section 70–350 m with mud motor using high-yield bentonite as drilling fluid. Heal loss zones with LCM and cement large losses as you go. Mud coolers used as required.
- Temperature and lithological logs are run.
- Run the surface casing and cement by the inner-sting method.
- Install another set of BOP´s. Test BOP´s.

ANCHOR CASING

- Drill the section 400–950 m with mud motor and mud as drilling fluid. Heal loss zones with LCM and cement large losses as you go. Mud coolers used as required.
- Temperature and lithological logs are run.
- Run the intermediate casing and cement by the inner-sting method.
- Install BOP´s and test.

INTERMEDIATE CASING

- Cool the well every two pipe joints while tripping in.
- Drill the section 800–2400 m with mud motor and mud as drilling fluid. Rotary table and Kelly can be used. Heal loss zones with LCM and cement large losses above say 1500 m as you go. Mud coolers used as required. When losses increase continue drilling with water only.
- Temperature and lithological logs are run.
- Run the intermediate casing. Cement with the inner-sting method with volume enough to reach up to the first big loss zone. While cementing continue pumping water from above. Cement from surface down the annulus until filled.
- Install the master valve and install the BOP stack.
- Drill out the float collar and float shoe pilot drill some 30 m into the formation with a 6-1/2” bit. This is to provide room for thermal expansion of the technical casing. Run a pack-off test.
- Run the technical casing 10 m below the shoe. Hang the casing from surface.

Coring below 2400 m

Coring commences at 2400 m and the well is cored to total depth in two parts, section I (2400–3500 m) and section II (3500–5000 m). In between the upper cored sections reamed out and the production casing landed. Figure 27 describes the sequence of drilling.

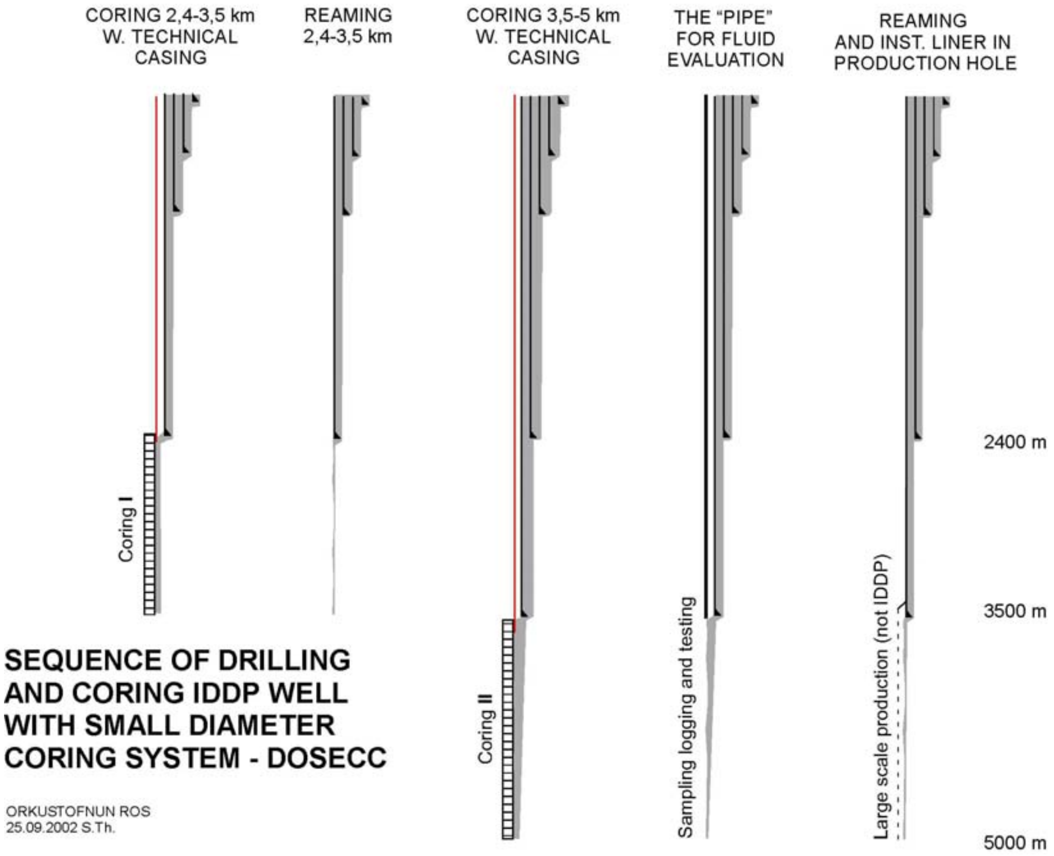


Figure 27. *Sequence of coring and drilling the IDDP well below 2400 m.*

CORING I

- Rig up coring unit.
- Install BOP´s for coring unit. Test.
- Continuously pilot core 2400–3500 m.
- Pump water on annulus by the core rod and also by the technical casing in an effort to maintain well full of water at ALL times.
- Run memory tool in core barrel for temperature and inclination.
- Pull out of hole.
- Log the hole.
- Remove 7–1/16” BOP´s
- Pull technical casing out of hole.
- Take out top drive of coring unit from mast.

PRODUCTION CASING

- Cool the well continuously with water while tripping in with top drive.
- Ream the cored hole with top-drive and tri-cone bit. Water used as drilling fluid.
- Drill the section 2400–3500 m with mud motor and mud as drilling fluid. Heal loss zones with LCM and cement large losses as you go. Mud coolers used as required. When losses increase continue drilling with water only.
- Temperature and lithological logs are run.
- Run the production casing. Cement with the inner-sting method with volume enough to reach up to the first big loss zone. While cementing through the string continue pumping

water to the annulus from above to stop the loss zone from healing. Pump cement then from surface down the annulus until the loss zone is filled to surface.

CORING II

- Reinstall coring unit in mast
- Install BOP´s for coring unit. Test.
- Continuously pilot core 3500–5000 m.
- Pump water on annulus by the core rod and also by the technical casing in an effort to maintain well full of water at ALL times.
- Run memory tool in core barrel for temperature and inclination, while temperatures allow.
- Pull out of hole.
- Log the hole, if possible.
- Remove 7-1/16” BOP´s
- Pull technical casing out of hole.
- Finish.

9 DRILLING EQUIPMENT AND MATERIALS

Rig selection

Following are the assumed minimum drilling unit requirements for well profile A and B (see 6.6 for casing program). For comparison Garden Denver 700E drilling rig “Jötunn” of Iceland Drilling Corporation Ltd.

Table 17. *Minimum requirement for drilling unit*

DRILLING UNIT	WELL PROFILE A Reamed 8 1/2" to TD	WELL PROFILE B Cored from 3500 to TD	"JÖTUNN" Gardner Denver 700E
PRINCIPALS:			
Year of make	-	-	1972
Last General Inspection/Maintenance	Less than 3 years ago	Less than 3 years ago	2002
Rig type	SCR Diesel-Electric	SCR Diesel-Electric	SCR Diesel-Electric
Rating	1500 hp	1000 hp	750 hp
Hook Load	300 ton	200 ton	180 ton
SUBSTRUCTURE:			
Type	-	-	box on box
Service temperature	- 20°C	- 20°C	- 20°C
Clear Working Height	6,7 m	6,7 m	5,8 m
Capacity	400 ton	300 ton	385 ton
MAST:			
Type	-	-	Telescopic
Service temperature	- 20°C	- 20°C	- 20°C
Height	40 m	40 m	40 m
Sheaves	4-6	4-6	4
Nominal Capacity	350 ton	250 ton	220 ton
Racking Capacity	5000 m	3500 m	3450 m

DRAWWORKS:			
Type	-	-	Gardner Denver 700E
Horsepower Rating	1500 hp	1000 hp	750 hp
Hoisting speeds	4	4	4
Main Brake	-	-	700 R Band Brake
Auxiliary Brake	-	-	40" hydromatic

Rotary Table:			
Type	-	-	Gardner Denver
Opening	27 1/2"	22 1/2"	22 1/2"
Drive	Independent	Independent	Independent
Nominal Rating Power	1000 hp	1000 hp	750 hp

Hook Block:			
Type:	-	-	BJ
Service temperature	- 20°C	- 20°C	- 20°C
Hook Load	350 ton	300 ton	300 ton

Top Drive:			
Type	-	-	-
Capacity	300 ton	200 ton	-
Horsepower Rating	700 hp	450 hp	-
Torque	4000 daN-m	2700 daN-m	-

Mud Pumps:	3	2	2
Type:	Triplex	Triplex	Triplex
Horsepower Rating	1000 hp	1000 hp	750 hp
Pressure Rating	340 bar / 5000 psi	340 bar / 5000 psi	340 bar / 5000 psi

Mud System:			
Mud Tank Capacity	120.000 l	100.000 l	80.000 l
Shale Shaker	2 pc linear	2 pc linear	1 pc linear
Desander and Desilter	yes	yes	yes

Power Pack:			
Type:	CAT	CAT	CAT 3508B
Skid mounted, field-units	yes	yes	yes
Silenced	yes	yes	yes
Continuous Output	4 x 682 kW	3 x 682 kW	3 x 682 kW

SCR-unit:			
Type:	-	-	Ross Hill model 1200
SCR	4 - BAY	4 - BAY	3 - BAY

Cementing Unit:			
Type	Land Unit	Land Unit	Land Unit
Automatic Control Density Tolerance	Preferable	Preferable	-
Continuous working Time	2 hours	2 hours	2 hours
RCM Cement Mixer:			
Mixing Capacity	0-2000 l/min	0-2000 l/min	0-2000 l/min

Fluid Displacement Tanks	2 x 1000 l	2 x 1000 l	2 x 850 l
Mixing Density	1 - 2 g/cm3	1 - 2 g/cm3	1 - 2 g/cm3
Mixing Centrifugal Pump	4 x 3 - 1500 l/min @ 8 bar	4 x 3 - 1500 l/min @ 8 bar	4 x 3 - 1500 l/min @ 8 bar
Recirculating Centrifugal Pump	5 x 4 - 2000 l/min @ 3 bar	5 x 4 - 2000 l/min @ 3 bar	5 x 4 - 2000 l/min @ 3 bar
Cementing Pump:			
Type	Triplex with plungers	Triplex with plungers	Triplex with plungers
Flow rate	Up to 3000 l/min	Up to 3000 l/min	Up to 3058 l/min
Max Pressure	400 bar	400 bar	425 bar
Horsepower Rating	400 hp	400 hp	400 hp
Cement Tanks Capacity	150 m3	150 m3	3 x 50 m3

Mud system

The mud tank should have a capacity of 80–100 m^3 with three compartments. The tank will have a sand trap, shaker desander, hydroclone desilter, two agitators, top and bottom mud guns, mixing hopper and centrifugal pumps. An extra tank is required for mud storage, and another tank to act as a surge- and emergency tank for cold water to kill the well. The water tank will be directly connected to the high-pressure cement pump that ties into to killing manifold.

Due to heating up of the circulated mud, cooling will have to be provided in three stages. Each mud cooler will have separate centrifugal pumps and normal mud circulation can continue with one or more of the coolers turned off. First diverting the flow after the shaker to a spray pond will cool the mud. Secondly the mud will be cooled in an open cooling tower between the first and second tanks. Finally the mud can be cooled in a water-cooled heat exchanger. The cooling effect may reach 3.3 MW$_t$, equivalent to cooling a flow of 40 l/s by 20°C.

Drilling fluids

9.1.1 Rotary drilling fluids

Selection of drilling fluids and hydraulic programmes should be prepared for every section. Water and/or water-based mud (bentonitic clay) may be used, mingled with polymers and LCM to ensure adequate hole cleaning. Heavy losses may occur, forcing use of cold water only. However using water-based mud should be attempted as deep as possible, using mud-cooling system on surface.

Section Well profile A - B	Estimated Max Pump rate l/min / gpm	Calculated Pressureloss in drillstring Bar / Psi	Drilling Fluid
1. Section: 26" - 21" Drilling to 400 m	3.000 790	67 979	Water based mud, mingled with polymers and LCM
2. Section: 21" - 17 1/2" Drilling to 800 m	3.000 790	86 1.250	Water based mud, mingled with polymers and LCM
3. Section: 17 1/2" - 12 1/4" Drilling to 2300 m	4.200 1.110	129 1.871	Preferably Water based mud, mingled with polymers and LCM
4. Section: 12 1/4" - 8 1/2" Drilling to 3500 m	3.000 790	130 1.884	Cold Water mingled with polymers and LCM
5. Section: 8 1/2" - 6 1/4" Drilling to 4-5000 m	2.400 635	109 1.579	Cold Water mingledwith polymers

Drilling in formation with formation temperature in excess of 500°C is always a challenge and this condition as extremely rare.

NEDO exploration well WD-1A in Kakkonda geothermal area, Japan is a well documented undertaken and probably the highest temperature well drilled to day with BHST at 500°C (932°F). This undertaken has demonstrated that a borehole can be drilled into formation temperature as high as 500°C, provided the well is cooled properly and conditioned to permit drilling with conventional methods.

Experience from well WD-1A is the basis for the drilling mud cooling system proposed for the project. The cooling system consists of two open type mud cooler, one closed loop mud cooler and four mud tanks, two of which in tandem and two mud pumps. Desander, desilter, microcyclone and centrifuge to minimize solid contents in the mud.

The evolution of geothermal drilling mud used in the Imperial Valley, California began with the first generation mud in 1976. The third generation was first used successfully in an exploratory well drilled in 1980. During the next decade the fluid has been utilized drilling over seventy-fife well with successful results from both operational and economical standpoint. The BHT´s in excess of 316°C (600°F).

The principal ingredients of third generation geothermal drilling fluid are bentonite as a viscosifying agent, a low molecule weight copolymer for high temperature deflocculation and rheological stability, sulfonated lignite and a modified vinyl copolymer for high temperature filtration control (H.E. Zilch et al. 1991, SPE 21786). This mud system maintains rheological stability as well as adequate filtration control. Decomposition temperature is in excess of 400°C (750°F).

9.1.2 Coring fluids

The drilling fluid used for coring is a water based polymer mix. This serves to lubricate and stabilize the coring string and maintain low torque. It is expected, because of the low pumping rates, that there will be no return to surface of the fluid, that it will all be lost in the hole. To maintain the well pressure, water can be pumped on the outside down the inner annulus between the drill rods and technical casing and also water may be pumped down the outer annulus between technical casing and the cemented casing.

9.1.3 Water supply system

An adequate supply of fresh cold water must be available at site at all times. Long sections of drilling with heavy losses or no return at all are foreseeable. Therefore the supply rate must be 80 l/s of fresh cold water. Generally the incoming water temperature is 4–6°C.

Two sets of supply pumps must be used, each having an independent power sources and two separate water supply lines. Length of water supply lines should be kept as short as possible.

Drill string / drill bit

- Drill pipes should be manufactured per API SP 5D, API SP7, API RP 7G (American Petroleum Institute) and IRP 1.8 (Canadian Industry Recommended Practices – Critical Sour Drilling).
- Grade should be SS-105 or equivalent. (Yield 105–120 ksi, tensile 115–140 ksi. Maximum hardness pipe body: 27 HRC. Maximum hardness tool joint: 30 HRC).
- Drill pipes internally coated. Coating should be able to withstand temperature of minimum 175°C. (e.g. TK-34)
- Hardbanding on tool joints should be flush.
- Used drill pipes should be tested according to T H Hill, Standard DS-1, Drill Stem Design and Inspection, Service Category 4, Premium Class.
- Drill bits will be journal bearing tri-cone with inserts and gauge protection, selected according to anticipated drilling conditions and experience gained from earlier drilling in the area.

Cementing

9.1.4 Loss zones

If loss zones have to be sealed of, then it is possible to seal zones off with cement. The size of operation has to be estimated from the volume lost in the zone and change of pressure in the well.

Cementing of loss zones is done through drill pipes, where the end of drill string is located close to the loss zone. The use of LCM materials has to be considered when the size of the loss has been estimated.

9.1.5 Casing cementing

First stage of casing cementing is done through drill string and float collar, the casing is cemented from bottom and up 300–500 m, then the casing has been anchored. Pumping cement slurry on the annulus in stages until adequate cement filling of annulus is obtained finishes the cement job.

Class G cement should be suitable with 40% silica flour, 2% expanded perlite, CRHT-1 high-temperature retarder, fluid loss additive like PSP-322, approx. 0.4 %.

Density of cement slurry should be kept relatively low to avoid problems in the cement job in this kind of formation, which is unconsolidated with fractures and water level way down. Density of slurry no higher then 1.65 kg/l is recommended.

It is recommended that some LCM, like coarse or flakes, would be available for mixing with the cement slurry.

10 WELL AND CORE LOGGING

Mud logging. On-site geologist

The main objectives of the mud logging are to collect information during drilling that can be used to create a geothermal model of the reservoir. This is done by identifying the geological control of permeability, detail geological structures and location of feed points. The rig crew while rotary drilling collects cutting samples every 2 m and the on-site geologist during a daytime visit makes the lithological description and prepares the daily report. The geologists usually rotate every week. The samples are then archived for further off-site investigations; microscope, XRD analysis, thin sections, fluid inclusions. The workflow for subsurface exploration during high-temperature drilling in Iceland is shown below. This general procedure will be followed for the IDDP well but special studies and other tests will be an add-on.

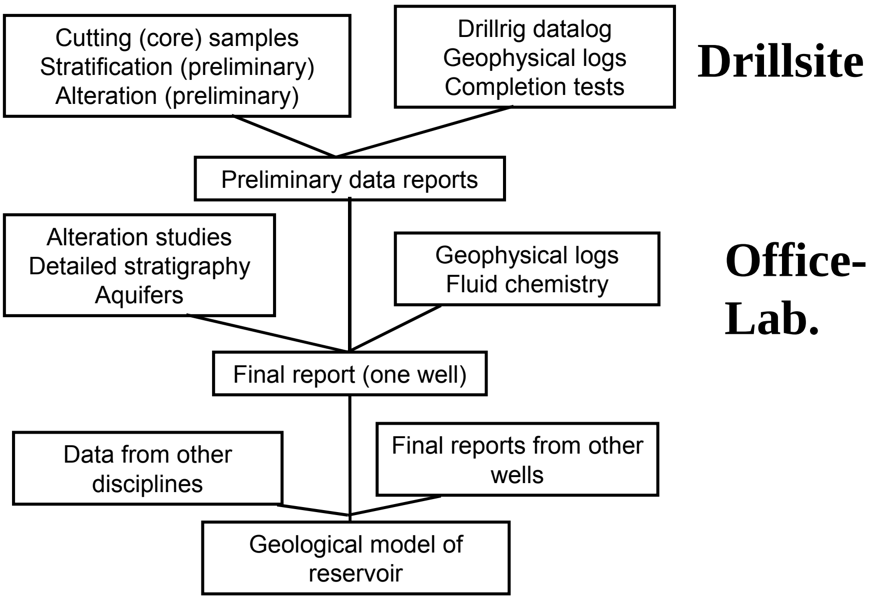


Figure 28. *Workflow for sub-surface exploration for high-temperature drilling.*

Identification of the temperature-alteration minerals provides important information on the temperature history for the reservoir, past and present. The main minerals are identified by microscopic investigations on-site and provide valuable information on the formation being drilled. These investigations can give early warning of abnormally high temperatures, loss zones or well stability problems. The temperature range for the main alteration minerals is shown in the Figure below, as this is the “key” to the interpretation of the temperature state of the hydrothermal system and its evolution.

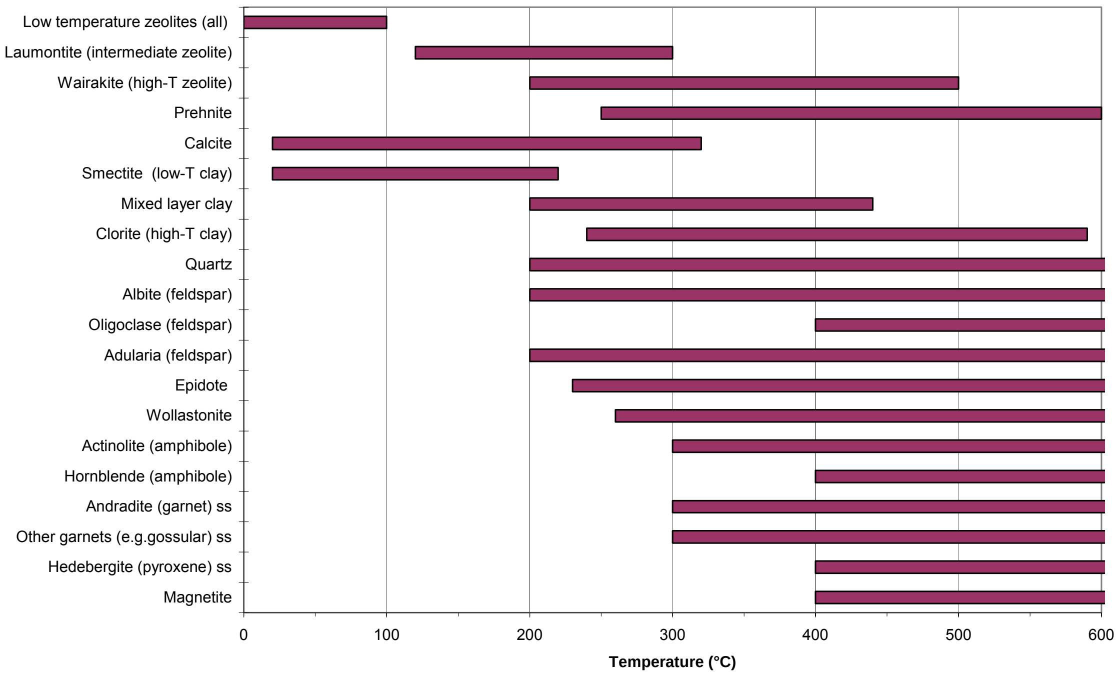


Figure 29. *Hydrothermal alteration minerals found at different temperatures (empirical).*

Core handling

While the well is being cored additional personnel is required to handle the core and log. The exact work to be performed on site is yet to be defined, but the basic core handling will be similar to the description Dennis Nielson gave for the HSDP at the IDDP workshop WS II. Once the drillers have removed the core the custody of the core is transferred to the science team. He divided the work of the science team into ten steps:

Table 18. *Core handling on site. Procedure used for the HSDP project (Dennis Nielson).*

Step 1: Core is washed and reviewed by logging team. Unusual features and contacts are identified.
Step 2: Each core run is placed on the table. Up hole orientation is checked and fractured pieces are reassembled. Red and blue scribe lines are made “Red on RIGHT looking up the core”. Fractured core is shrink-wrapped to preserve its structural integrity when needed
Step 3: Core is split into two portions on the slab saw: 1/3 for archive and 2/3 for working samples.
Step 4: Slabbed core are dried in shipping containers in which vented propane heaters have been installed.
Step 5: Boxes are digitally photographed and input into DIS database for annotation during logging.
Step 6: Logging descriptions are input into DIS database. Each logged box includes tow parts: a completed standardized logging form and an annotated photo.
Step: 7: High-resolution digital photos of slabbed core faces are scanned using the DTM CoreScan Colur unit. Whole, unslabbed core can also be scanned.
Step 8: Chief Logger conducts quality control over core logs. Each log and annotated photo are reviewed before litologic units are defined.
Step 9: Samples from each litologic unit for the core reference suite are collected.
Step 10: Core boxes are packed and the shipped for further analyses and dissemination to other investigators.

Wireline logging

Orkustofnun has since 1976 operated logging trucks for electrical instruments to log geothermal wells. Before that time, termistors were used for temperature logging as early as 1947 and after 1960 mechanical gauges were added from Amerada and Kuster. The first electrical logging equipment was bought from Gearhart-Owen Industry and their subsidiaries. By 1980 Orkustofnun was operating three logging trucks, two with single drum for electrical cable and one with double drums for both electrical cable and wireline. Two of those units have been renewed, but one is still in use. It has a small drum capacity around 1000 m of electrical cable and is not listed with the currently available equipment. For the last six years the logging activity at Orkustofnun has average about 400 km per year.

The logging equipment that Orkustofnun currently possesses is listed in the following tables. There are two logging trucks, the bigger truck is German made MAN chassis with single drum measuring unit and cabin made by Pengo in U.S.A. The smaller truck is U.S.A made Ford Econoline 350 chassis with double drum measuring unit designed at Orkustofnun. The current length of the electrical cables on the trucks is just over 3000 m on the bigger truck and 2000 m on the smaller one. The older electrical gauges with pulse telemetry were made by Gearhart-Owen Industry (GO) while the newer ones are made by Computalog (CL) and Comprobe (CP). The tools with the digital telemetry are made by Robertson Geologging (RG). The newer wireline gauges are made by Kuster Company, while the older ones are also from Geophysical Research Corporation.

The temperature limitation for most of the electronic measuring tools owned by Orkustofnun is below 150°C. Nevertheless, most high and low enthalpy wells drilled in Iceland during the last 25 years have been logged with them. The reason being that during drilling the high enthalpy wells are cooled well below the temperature limitation of the tools. The cooling is maintained through out the drilling and for some time after the completion of the wells, which allows downhole lithological logging, identification of main flow zones and estimations of transmissivity. Figures 31 and 32 illustrate the temperature conditions that can normally be expected in a high enthalpy geothermal well in Iceland. Figure 31 indicates a loss zone deep in the well which makes the cooling more effective, while Figure 32 indicates at least two flow zones where the upper one feeds into the well and the deeper one accept that fluid along with some circulation loss.

Logs normally run at the end of drilling of a geothermal well in Iceland include temperature, caliper, neutron-neutron, natural gamma, normal resistivity and pressure. After casings are cemented a cement bond log is run nearly without exception in high enthalpy wells. Logging suits for low enthalpy wells is basically the same. As high enthalpy wells warm up after completion the temperature becomes higher than the electrical tools can tolerate. After that mechanical gauges are used to measure temperature and pressure in the wells.

The temperature limit for the existing logging tools is less than 350°C and Orkustofnun has no plans to acquire tools with higher tolerance. Therefore, it will be necessary, possibly for the deeper part of the IDDP well and for all extreme conditions expected to obtain measuring tools and cables through international cooperation. Availability of such high temperature tools is not clear as most of them are still in a developing phase. Their requirement will, however, depend on the scientific objectives and the access that individual scientist participating in the project have to them.

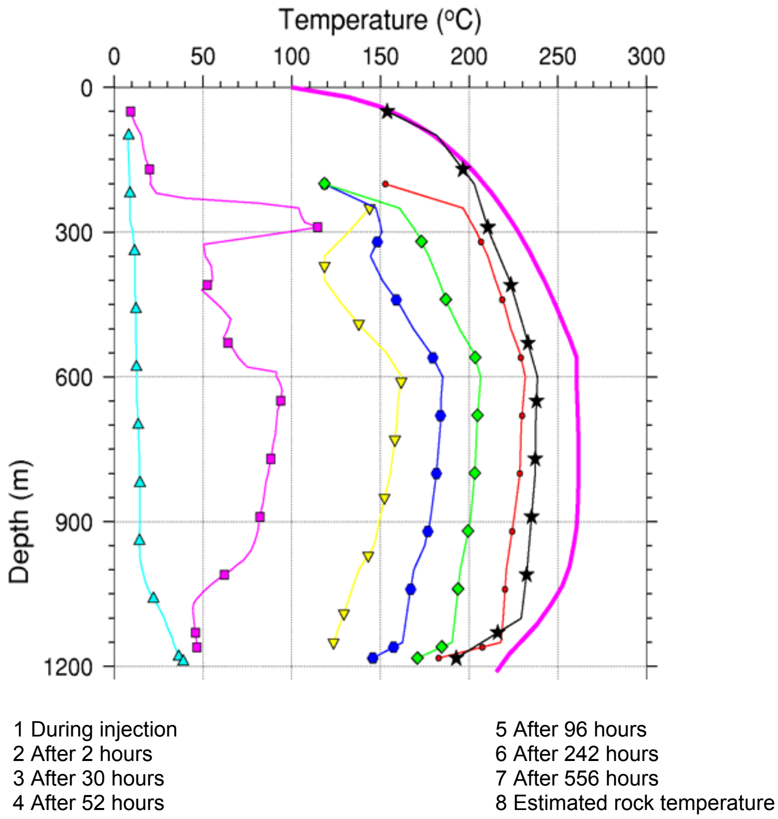


Figure 30. *Temperature at end of drilling and during recovery.*

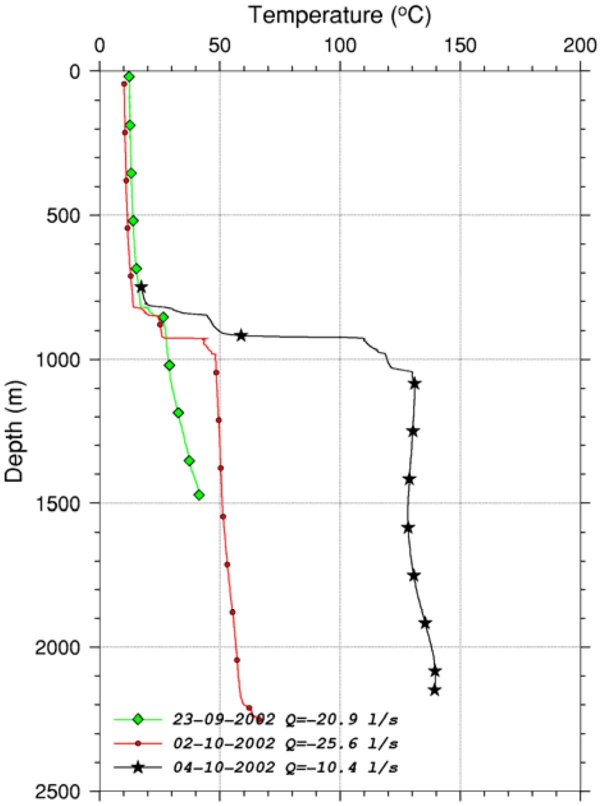


Figure 31. *Temperature in well while pumping from top.*

Table 19. *Logging trucks operated by Orkustofnun 2002.*

Logging truck Name	Mfg.	Year	Line diameter OD (mm)	Depth capacity (m)	Line speed Max (m/min)	Slow speed (m/min)	Encoder (pulse/m)	Weight in water (kg)
MAN - R47454	Pengo	1986	5/16" (8.20 mm)	3000 (5000)	90	1-2	400	229 kg/km Martin-Decker indic.
Ecoline NB-765 double drum	Orkustofnun	1995	7/32" (5.66 mm)	2000 (2500)	50	1-2	500 optional 1000	107 kg/km Load-cell
			0.092"	3000 (3500)	90	2		22.6 lbs/1000ft Load-cell

Table 20. *Logging cables in use.*

Mfg and Logging cable or wireline	Year	Line diameter OD (mm)	Length (m)	Cond. (#)	Material	Max T (°C)	Breaking strength (kg)
Rochester Corp. 7-H-314K	1997	5/16" (8.20 mm)	>3000	7	#22 AWG 7/0.010" Bare Copper dia.0.76 mm Ins. 0.014" wall ETFE dia. 1.47 mm Cdr. Dc-res 54.5 ohm/km Armor Dc-res 8.2 ohm/km Cable head GO-type 1" 4 cond. female optional GO-type 1-1/2" 7 cond. female	246	42.7 kN 17.1 kN work load
Rochester Corp. 4-H-220K	1995	7/32" (5.66 mm)	>2000	4	#24 AWG 7/0.008" Bare Copper dia. 0.61 mm Ins. 0.013" wall PFA dia. 1.27 mm Cdr. Dc-res 85.3 ohm/km Armor Dc-res 16.4 ohm/km Cable head GO-type 1" 4 cond. female	246	20.5 kN 8.2 kN work load
(Kuster) wireline	2000	0.092" (2.33 mm)	>3000	0	Stainless steel (316)		1040 lbs.

Table 21. *Logging tools in use by Orkustofnun 2002.*

Logging tool Name	Qty	Mfg.	Year	Range	Output signal	Accuracy (% fs)	Max temp. (°C)	Diameter OD (mm)	Length (m)	Weight (kg)	El. cable # lines
Temperature Tools	5	GO/CL	2000	0-150 °C	pulses	+/- 1.5 °C	150	1-3/8"	0.9-1.2	6	1
Calipers X-Y	2	GO/CL	2002	4-30", 6-60"	pulses	+/- 0.25"	120-150	3-1/2"	1,4	38	1
Calipers 3-arm	2	GO/CP	2002	2-30"	pulses		150	1-5/8"	1,7	12	1
Pressure Tool	1	OS	1989	0-200 bar	pulses		120	1-3/8"	1	6	1
Neutron NN+Nat Gamma	2	GO	1977		pulses		100	1-5/8"	1,8	15	1
Normal Res 16"+64"+SP	3	OS	1995		analog/pulses		140	2"	2	6	4
STD Bond Tool	1	CL	1998		pulses		150	2-3/4"	2	40	1
Fluid sampler	1	GO	1985				120	2"	2,5	15	1
Magnetic single shot tool	1	Totco	1982	0-30°	chart	1°	200	1-5/8"	2,2	20	0
Televiewer Accustic	1	RG	2001		digital		100	1-9/16"	1,7	12	3
Induction Tool	1	RG	2002		digital		105	1-1/2"	2,1	10	3
Neutron Dual+Nat Gamma	1	RG	2002		digital		125	2-17/32"	2	30	3
Mech. Temperature Tools	5	Kuster	1998	90-350 °C	chart	+/- 3 °C	360	1-1/4"	1,5	7	0
Mech. Pressure Tools	3	Kuster	1998	0-200 bar	chart	+/- 1 bar	360	1-1/4"	1,7	8	0
GO-Devils (Width baskets)											
Sinker bars											

Use of Development Logging Tools

At present there are no commercially available logging tools, to our knowledge, that can measure temperatures or pressures above the critical point. The highest rated tools are the Kuster mechanical T & P tool rated to 360°C. In order to confirm that the well has a temperature above these conditions new tools have to be introduced. In Japan the only temperature logging at these temperatures were made by lowering a tool with metal “pills” of different melting temperatures, a so called melting gauge. Suggestions were made for installing a memory tool to run into the hole inside the core barrel. It would thus be retrieved and the information downloaded after each run of the core barrel. Other possibilities for logging the well where the temperature is the highest will be investigated as part of future preparation and through consultation with the scientists. It is expected that they will provide the logging tools, but the wireline unit will be on site. The cost for some such logging is included (time and wireline charges) in the price estimate, but not rental of the tools.

11 DRILLING INFORMATION SYSTEM

Rig instrumentation

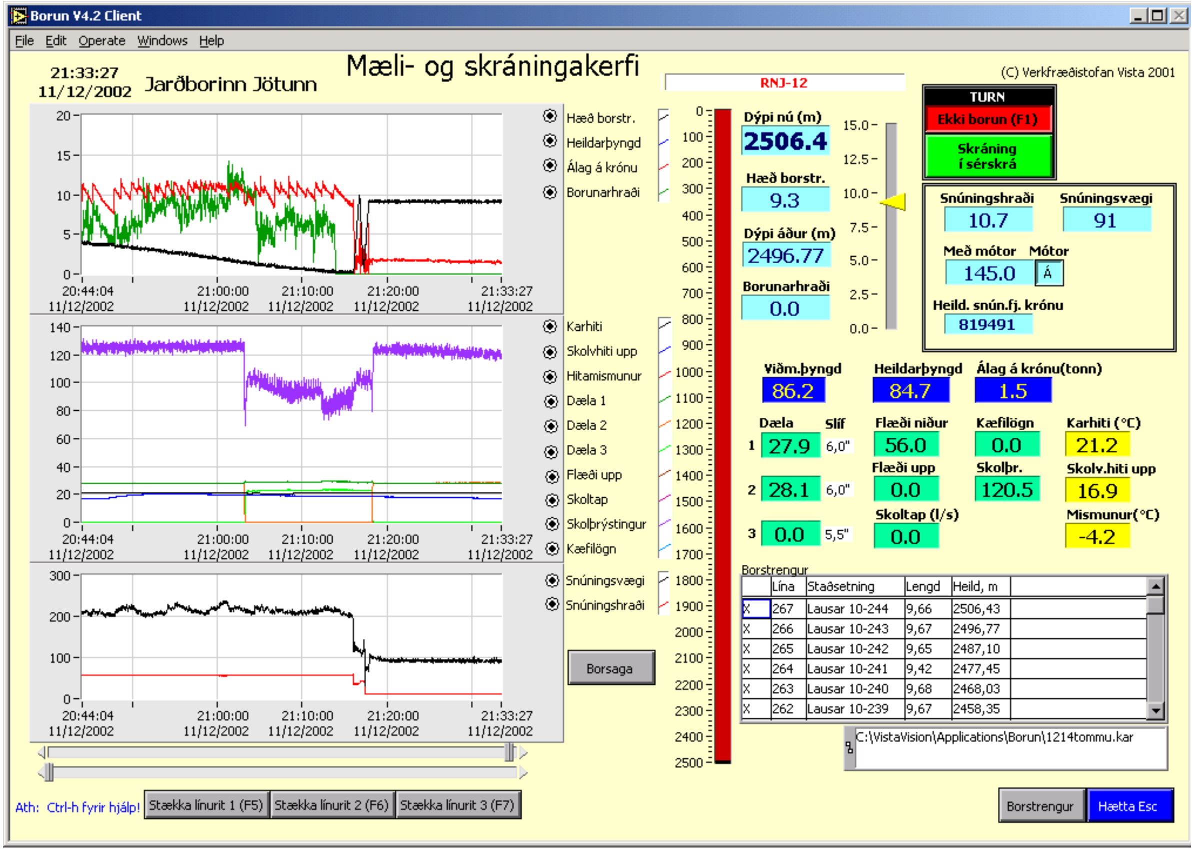
A modern rig instrumentation system is required to assist the drilling crew in their work and to provide the mud logging data. Some of this data is valuable to the scientific investigations and all the data will be made available to IDDP participants on site over the wireless network. Selected parts, as decided by the principal investigators, will be transmitted to the DIS system and be accessible over the net.

For reference a system made in Iceland for the rig Jötunn is displayed. The on-site data handling and visualization software used for the rig instrumentation is National Instruments LabVIEW. The logging rate is 1 second and display refresh rate 5 seconds shows the average. Historic data is stored every 20 seconds.

The following table describes the measurement requirements foreseen for the IDDP drilling rig (not the coring unit) and indicates which of the sensors are now on Jötunn.

Table 22. *Rig instrumentation requirements for IDDP rotary drilling.*

PARAMETER	Meas./ Calc.	Graphed	Range	SI units
EXISTING ON JÖTUNN				
Standpipe Pressure	M	Yes	0-250	bar
Flow from MP1	M	Yes		l/s
Flow from MP2	M	Yes		l/s
Flow from MP3	M	Yes		l/s
Total Flow from Mud Pumps	M	Yes		l/s
Mud temp. at standpipe	M	Yes	0-100	°C
Mud temp. at flowline	M	Yes	0-100	°C
Wellhead pressure	M	Yes	0-100	bar
Block Postition	M	Yes	0-40	m
Rotary Torque	M	Yes	0-1000	A
Rotary speed	M	Yes	0-200	rpm
Weight on Bit	C	Yes	0-250	tonne
Hookload	M	Yes	0-250	tonne
Block Position	M	No	0-30	m
Rate of Penetration	C	Yes	0-100	m/h
Total Hole Depth	C	No	0-5000	m
ADDITIONAL SENSORS				
Mud Flow Out	M	Yes	100	l/s
Volume for each Pit	M	No	100	m^3
Total Active Pit Volume	C	No	150	m^3
Total Pit Volume	C	No	150	m^3
Gain/Loss Flow	C	Yes	x	%
Gain/Loss Active Volume	C	No		m^3
Trip Tank Volume	M	No	10	m^3
Cathead Tong Torque	M	No	200	kN-m
Casing Tong Torque	M	No	200	kN-m



Dýpi nú (m) 2506.4

Hæð borstr. 9.3

Dýpi áður (m) 2496.77

Borunarhraði 0.0

Snúningshraði 10.7

Snúningsvægi 91

Með mótor 145.0 Mótor Á

Heild. snún.fj. krónu 819491

Viðm.þyngd 86.2

Heildarþyngd 84.7

Álag á krónu(tonn) 1.5

Dæla		Slíf		Kæfilögn	Karhiti (°C)
1	27.9	6,0"	Flæði niður 56.0	0.0	21.2
2	28.1	6,0"	Flæði upp 0.0	Skolþr. 120.5	Skolv.hiti upp 16.9
3	0.0	5,5"	Skoltap (l/s) 0.0		Mismunur(°C) -4.2

Borstrengur

	Lína	Staðsetning	Lengd	Heild, m
X	267	Lausar 10-244	9,66	2506,43
X	266	Lausar 10-243	9,67	2496,77
X	265	Lausar 10-242	9,65	2487,10
X	264	Lausar 10-241	9,42	2477,45
X	263	Lausar 10-240	9,68	2468,03
X	262	Lausar 10-239	9,67	2458,35

C:\VistaVision\Applications\Borun\1214tommu.kar

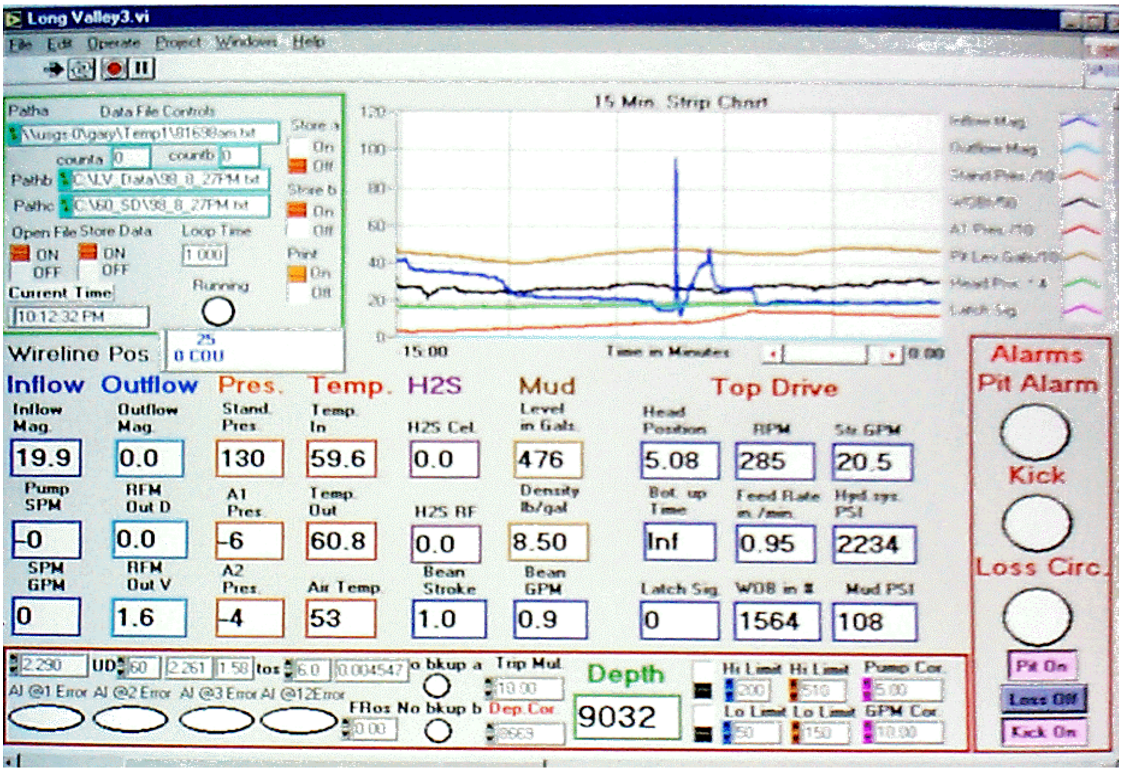
Figure 32. *Drillers data display on Jötunn rig (Jarðboranir).*

Coring unit instrumentation

The coring system will have additional sensors and as in the case of the DOSECC unit it has its own self-supporting system located in the core-drillers control cabin. This system is also programmed in LabVIEW. Data from these two systems will be merged as may be required for on-site viewing and parts of the data will be added to the DIS database for viewing over the Internet.

Table 23. *Instrumentation on the DOSECC coring unit.*

Wireline Counter, Rate and Weight Indicator
String/Bit Weight
Rotation RPM
Pump GPM (2)
Hydraulic Feed Pressure, Mud Pump Pressure
Drill Head Position / Feed Rate



Paths Data File Controls
\\usgs-0\gary\Temp1\81638am.txt
countа 0 countb 0
Pathb C:\LV_Data\98_8_27PM.txt
Pathc C:\60_SD\98_8_27PM.txt
Open File ON OFF
Store Data ON OFF
Loop Time 1.000
Current Time 10:12:32 PM
Wireline Pos 25 0 COU

Inflow	Outflow	Pres.	Temp.	H2S	Mud	Top Drive		
Inflow Mag 19.9	Outflow Mag 0.0	Stand Pres 130	Temp In 59.6	H2S Cel 0.0	Level in Gals 476	Head Position 5.08	RPM 285	Str GPM 20.5
Pump SPM -0	RFM Out D 0.0	A1 Pres -6	Temp Out 60.8	H2S RF 0.0	Density lb/gal 8.50	Bot. up Time Inf	Feed Rate in /min 0.95	Hyd sys PSI 2234
SPM GPM 0	RFM Out V 1.6	A2 Pres -4	Air Temp 53	Bean Stroke 1.0	Bean GPM 0.9	Latch Sig 0	WOB in # 1564	Mud PSI 108

Depth 9032
Hi Limit 200 Hi Limit 510 Pump Cor 5.00
Lo Limit 50 Lo Limit 150 GPM Cor 10.00

Figure 33. *Drillers data display on the DOSECC coring unit (DOSECC).*

On-site ICDP drilling information system (DISGFZ)

One member of the IDDP team will be a Data Curator who will have the responsibility to coordinate the data collection and DIS database and manage its distribution. To assist in this the drilling information system designed by GFZ in Potsdam and used on ICDP projects will be used. A thorough description is given on the ICDP home page: www.icdp.gfz-potsdam.de/html/dis/news.html. The following description is borrowed from there.

The objective of the DISGFZ system is to provide a comprehensive data and information management for continental scientific drilling projects is the main objective of the Information Network of the Continental Scientific Drilling Program ICDP. The Information Network consists of IT-services supporting:

- the capture of scientific drilling data using special drilling information systems DIS,
- the dissemination of project information by the ICDP Clearinghouse,
- the integrated evaluation and analysis of data supported by the ICDP Data Warehouse.

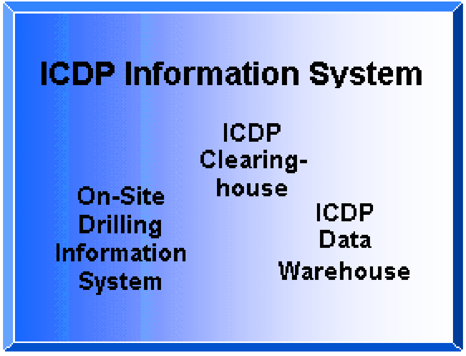


Figure 34. *General scheme of ICDP Information System (GFZ).*

DIS is a PC based MS-ACCESS data management application. A central part of DIS is a set of data structures (templates) typical for scientific drilling purposes. These templates can be adapted according to the demands of a certain project. Even completely new data structures can be created. After adaptation of an individual DIS, the application itself is the user interface for data input and output, completed by visualization tools such as GeoLogGFZ. The first field test was performed on the Long Valley Coring Project during summer 1998. The second test phase is currently the Hawaiian Scientific Drilling Project (HSDP), which started in March 1999.

The on-site configuration of HSDP DIS consists of one dedicated Windows NT 4.0 server, and four clients (Windows NT and Windows 98), connected by a twisted pair ethernet network using TCP/IP. Mobile systems like lap tops can be easily integrated. Three of the clients are mainly used for DIS data entry, the forth is the DMT® CoreScan Colour System, which is also directly linked to the DIS database. A fast internet connection is used for the daily update of the HSDP project Web pages on the ICDP Web server at GFZ Potsdam (http://icdp.gfz-potsdam.de).

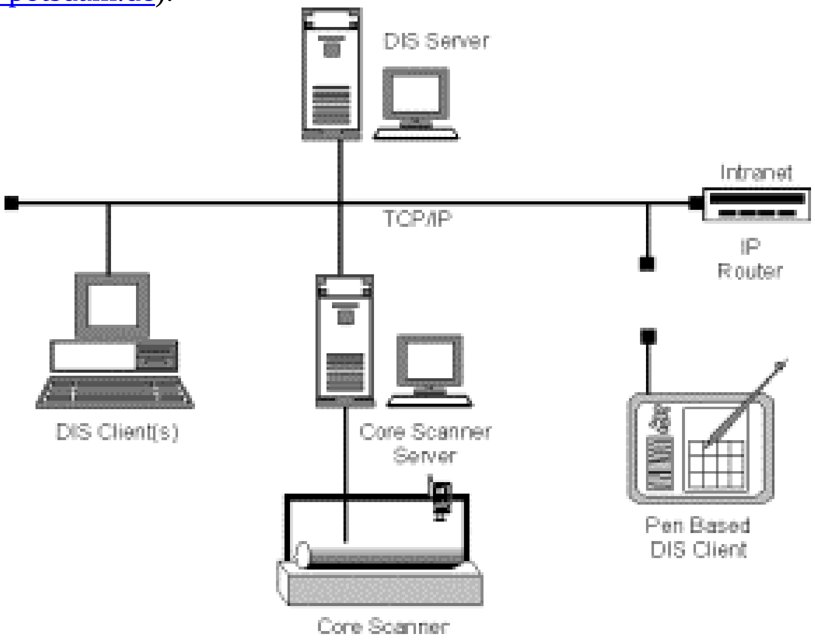


Figure 35. *Principle configuration of an on-site DIS network (GFZ)*.

The data model for the current HSDP drilling embraces:

- a picture archive for core box and core scan images,
- a core archive for the complete core recovery of the drilling,
- a sample archive for all samples taken from the cores,
- the lithological reference profile with the lithological description of all Litho Units,
- a borehole logging archive for all borehole measurements,
- and a drilling engineering archive for the daily drilling reports, and the online measurements of drilling parameter.

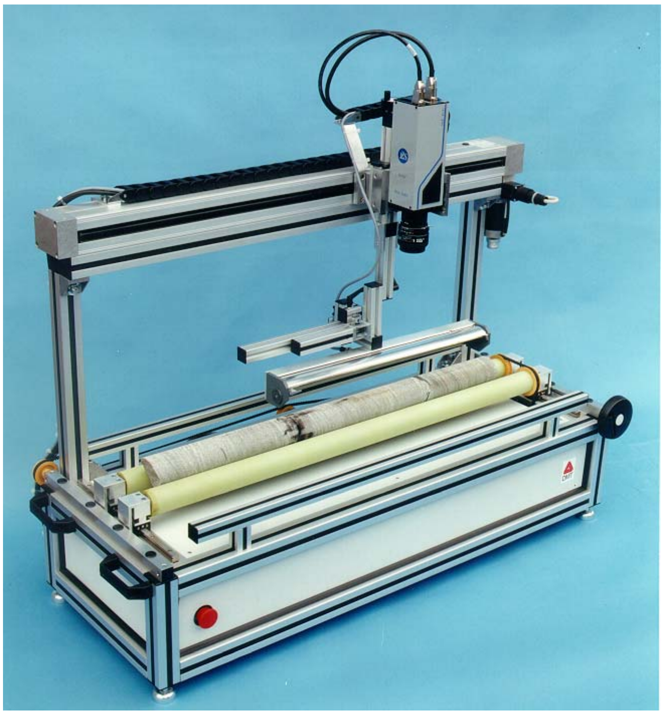


Figure 36. *The DMT® CoreScan Colour System (GFZ).*

There are six information classes accessible in DISGFZ over the Internet:

- CoreArc (all information related to core runs, core boxes, litho units, samples)
- Analysis (all information related to lab data)
- Borehole (all information related to borehole measurements)
- Drilling (all information related to drilling engineering)
- Well (all information related to the location)
- PicArc (all information related to the picture archive)

12 SITE FACILITIES

Drill site and access roads

A new drill site will be prepared, having a size of 100 x 60 m, and an access road suitable to carry the heavy loads and passable by a passenger car. Outside this area there is no activity. A deep concrete cellar is by the well to accommodate the wellhead, as the rig substructure is not high enough to accommodate the tall BOP stack. The mousehole, rathole and conductor will all be in place before the rig moves in. The site is compacted to support the rig load and has a gravel surface. A plastic lined mud pit is made to receive the cuttings and overflow from the mud tanks. The large cuttings settle in the earthen mud pit and the overflow is disposed via an excavated channel or by pumping to a to a natural run-off or disposal area. There is secondary containment for fuel and oils. Parts of the drill site around the engines are also covered with thick plastic film. All runoff around the engines and equipment that may leak oil is thus collected and network of drainpipes lead to a large buried tank that is an oil trap.

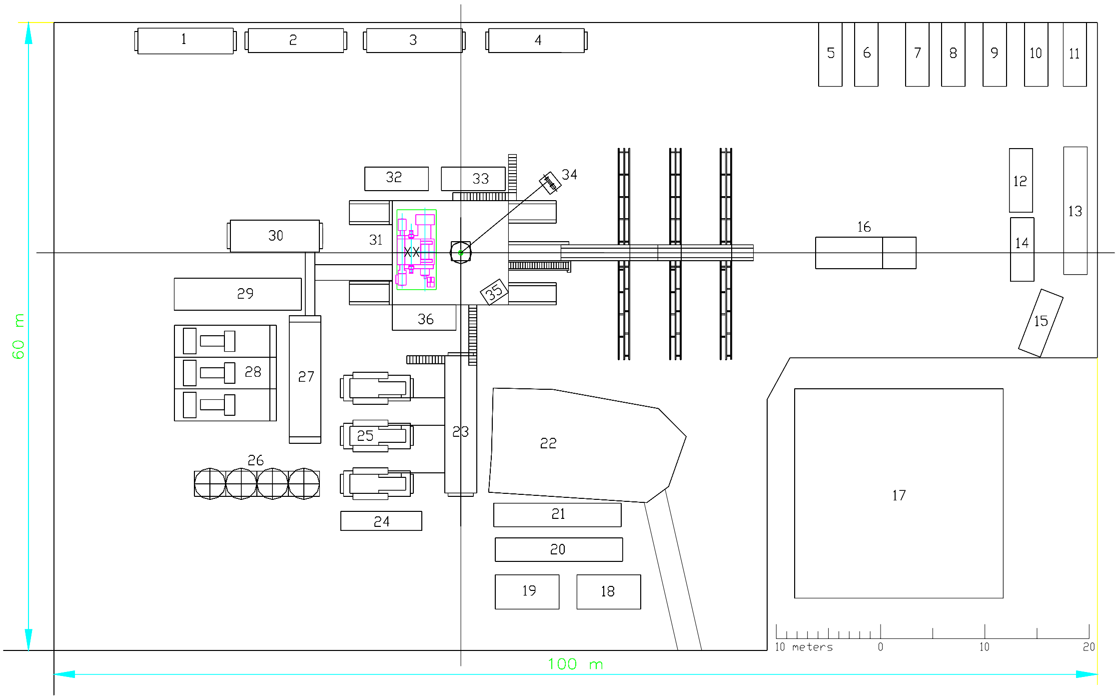


Figure 37. *Proposed lay-out of drill site. Outer dimensions 100 x 60 m.*

Table 24. *Major equipment and site facilities. Numbers refer to the drawing above.*

1	Utilities, toilet, shower	20	Mud tank
2	Office Rig Mechanical Eng.	21	Water storage
3	Office Tool Pusher	22	Mud pit
4	Coffee house, rig crew	23	Main mud tank
5	Project Mgr. and Drilling Eng.	24	Cement pump
6	Core lab.	25	Mud pumps 3 units
7	Core lab.	26	Cement tanks
8	Core handling, saw	27	SCR electrical controls
9	Core storage and drying	28	Diesel power units
10	Storage for Science team	29	Oil tank
11	DOSECC container	30	Work and tool shop
12	DOSECC office	31	Draw works
13	DOSECC container	32	DOSECC Workshop
14	Field lab. Mud logger	33	DOSECC Power Packs
15	Coffee house, science team	34	DOSECC Wire line Winch
16	Logging truck	35	DOSECC dog house
17	Spray cooling pond 20x20 m	36	Drillers dog house
18	Mud cooler, draft type		
19	Mud cooler, heat exchanger		

Office and lab space

Office and laboratory space will be in portable container type buildings. The routine mud logging and cutting analysis will take place in the existing container used for high-temperature drilling, and the core analysis and IDDP science will be in two other portable labs. The third container will be for dining and serve as a meeting place. A catering company brings in the food. For the day crew two hot meals and enough sandwiches and cakes for three coffee breaks.

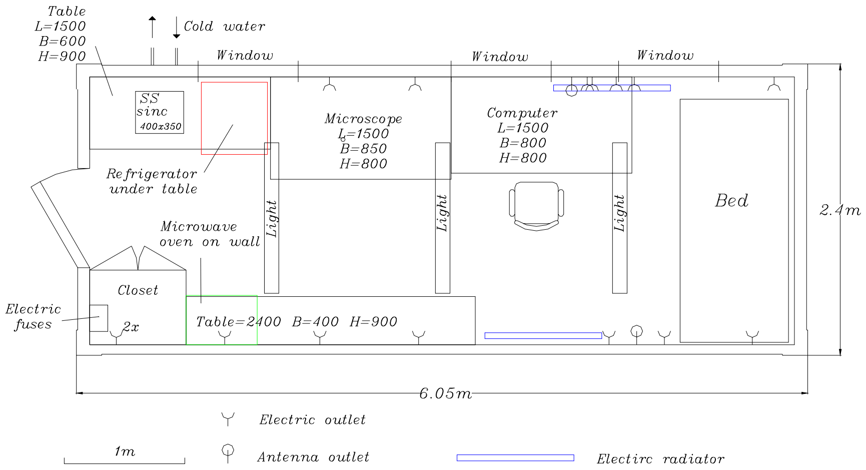


Figure 38. *Lay-out of mud logging field lab. Other labs will be similar but with no beds.*

The following description for additional office and lab space was provided by Ronald Conze Information Manager of Operational Support Group ICDP GeoForschungsZentrum Potsdam. The offices and labs should be with:

- Internal thin ethernet and maybe wireless internet connection internet uplink to the outer world for the IDDP-DIS it is recommended to have a well equipped powerful workstation (state-of-the-art PC) including standard devices like printer, scanner, CD-recorder etc. (specific details of the configuration and software needed can be provided when it will be purchased), and consumables like paper, CDs, floppies etc.
- For the core and cuttings logging, the fluid inclusion measurements and so on according PCs/laptops provided by IDDP or the projects.
- For the core scanner a stable table of about 2.5 to 3 m length would be necessary at a dry and normal air conditioned lab space using 220V 50 Hz.
- For the GeoTek system a space of at least 4 m length and a place for computer, and controlling devices at a dry and normal air conditioned lab space. (GeoTek sensors are: magn. susceptibility, video scan, p-wave, gamma density (porosity), natural gamma)
- For imaging the core boxes you will need according space with a fixed mounted digital camera, and good lights.
- Suitable undisturbed power supplies for the computer and scanner devices.

Core handling and storage

The facilities required by the Science Team for core handling and storage (see chapter on Core Handling) includes a space for washing the core, to mark it, cut lengthwise and then to box. This rough work will be done in a freight container to provide shelter. Another heated container is required for drying the core and core storage. The core scanning, microscopic investigations and core description is done in the two field labs dedicated to that purpose.

Telecommunications

The drilling rig PC-server will be connected continuously to the Internet via a private microwave link (256 Kbps or 2 Mbps). Such a network has been in place on drill sites for over a year and has been found to be reliable. On-site there is a Wi-Fi (IEEE 802.11b) wireless network for the labs and DIS system. The wireless system is also accessible by the whole IDDP Science Team through their mobile computers. At present the rig instrument panel can be viewed on-site over the wireless network and data downloaded. The same is available off-site via the Internet through a Virtual Private Network (VPN) connection. This system also handles all E-mail traffic. All drill sites have GSM (900/1800) coverage for mobile phones but the roads to the sites have sketchy coverage.

13 MANPOWER

The on-site manpower requirements have been estimated. As can be seen from the table below the requirements go up while the well is being cored. The cost estimate is based on this estimate of manpower requirements but cost of the drilling crew and coring crew is included in the per diem rig rate. The cost estimate is broken down into three periods: a) for period of rotary drilling, b) for period of coring, c) other costs. These other costs are not directly related to the number of rig working days and are to cover the cost of training, mobilization, report writing off-site etc.

Table 25. *Estimated on-site manpower requirements, IDDP drilling.*

PERSONS	ROTARY DRILLING		CORING	
	Daytime	Nighttime	Daytime	Nighttime
Project office and supervision				
PI - Project Manager	1	On callout	1	On callout
Drililng Engineer	1	On callout	1	On callout
Mud Engineer	1	On callout	1	1
Drilling crew				
Toolpusher	1	1	1	1
Driller	1	1	1	1
Mechanic	1	1	1	1
Roughnecks	4	4	4	4
Coring crew				
Coring supervisor			1	On callout
Diamond driller			1	1
Mud logging and well logging				
Site geologist (mud logger)	1	On callout	1	On callout
Wireline loggers	2	On callout	1	On callout
IDDP Science team				
Data curator	1		1	
Scientists			2	
Assistants	1		3	
Total personnel on site	15	7	20	9

14 ENVIRONMENTAL IMPACT OF DRILLING

Since 1994, drilling of production and research wells in high-temperature geothermal fields in Iceland has been an issue of Environmental Impact Assessment (EIA) Act. This also applies to the proposed IDDP well. According to the EIA Act, authorities are not allowed to permit projects subject to the Act unless an assessment of its environmental impact has been carried out. The objective of this chapter is to provide a simple overview of the current EIA Act and its practical application

14.1 The Environmental Impact Assessment Act

Geothermal drilling in Iceland is an issue of the current Environmental Impact Assessment Act No 106/2000 and the associated regulations. Deep drilling of production and research wells in high-temperature geothermal regions is classified according to Article 6, *Projects which may be subject to environmental impact assessment.* Projects under this category are assessed on a case-by-case basis with regard to the nature, size and location to determine whether they shall be subject to an environmental impact assessment pursuant to this Act.

Below is a brief summary of the Environmental Impact Assessment Act. The Environmental Impact Assessment process is also discussed in chapter 8 (Environmental Issues) in Part I of this feasibility report.

1. *Notification [week 0]*. Developers have to notify the Planning Agency about all proposed deep-drilling projects. The notification has to include a description of the proposed project, the scope of process and operation, information on how the project will comply with current development plans, environmental description of the project site, description of the main environmental impact etc.
2. *Assessment of notification [weeks 0-4]*. The Planning Agency will assess the available data and seek the opinion of the granters of consent (e.g. the local authority and the minister for industry and commerce) and others, depending on the nature of the project. For geothermal drilling projects these will typically include, the National Energy Authority and the National Environmental Agency. The developer will have the opportunity to reply to any reference made at this level.
3. *Decision on EIA [week 4–5]*. Within four weeks, the Planning Agency will decide whether the project shall be subject to environmental impact assessment or not. The Planning Agency shall inform the parties concerned of its conclusion and make it known to the general public, e.g. by publishing on the Agency’s official web site.
4. *Appeal [week 5–8]*. Within four weeks from the Planning Agency’s decision, anyone, including the developer, can appeal the decision to the minister for the environment.
5. *Ruling by the Minister for the Environment [week 9–12]*: The minister shall issue a reasoned ruling within four weeks from the expiry of the time limit for complaints.

If the Planning Agency (and/or the minister for the environment) concludes that the drilling project should be a subject to an environmental impact assessment, the formal EIA process starts:

6. *Scoping Document proposal [week 0]*. The developer shall propose a *Scoping Document* to the Planning Agency where he describes the project, the proposed project site and alternatives, which could be considered and provides information on the planning of the

project site and how the project will comply with the developer's plans. The Scoping Document shall also propose which aspects of the project and the environment should be emphasized, described what data is already available and propose a plan for making information available. The developer has to consult with the Planning Agency and present the Scoping Document proposal to both the parties who are to give an opinion on it and to the general public. The Planning Agency shall seek the opinion of the general public, the granters of consent and other official parties and the response of the developer to their remarks.

7. *Decision on the Scoping Document proposal [week 0–4]*. Within four weeks, the Planning Agency will decide on the Scoping Document proposal. If the Agency does not agree with the proposal, it shall instruct the developer how the proposed assessment plan should be further elaborated. If the Agency agrees with the proposal it has to inform the granters of consent and other parties who are to give an opinion.
8. *Environmental Impact Assessment study (EIA) [week 0]*. The EIA study has to be in accordance with the Scoping Document. The EIA shall specify cumulative and synergic effects, both direct and indirect, which the proposed project and the resulting activities may have on the environment. Furthermore, the EIA study shall also specify and the interaction of the individual environmental factors. It shall explain upon what premises the assessment is based and describe what aspects of the project are regarded most likely to affect the environment, including its size, design and location, and compliance with development plans. The main alternatives and mitigation measured and their environmental effects, have to be explained and compared.
9. *Assessment of the EIA requirements [weeks 0–2]*. Within 2 weeks of receiving the EIA study, the Planning Agency shall assess weather it fulfils the official requirements and is in accordance with the Scoping Document.
10. *Publicity and presentation of the EIA study [weeks 2–8]*. When the Planning Agency has accepted that the EIA study is in accordance with the Scoping Document, it shall advertise the EIA study both nation-wide as well as locally and the developer has to present the study in consultation with the Planning Agency. The EIA study has to be accessible at a location near to the project site (typically at the local library) and at the Planning Agency's office for six weeks.
11. *Examination by the Planning Agency [weeks 2–12]*. During that six weeks period, anyone can make written comments to the Planning Agency and the Agency shall seek the opinion of the granters of consent and other parties as appropriate. The developer will have the opportunity to respond to any official opinion or comment on the EIA study. Within four weeks after the period to comment on the project, the Planning Agency will study the EIA, opinions, comments and the response from the developer. Often, the Agency seeks expert evaluation from independent specialists on certain issues.
12. *Ruling by the Planning Agency [week 12]*. The ruling shall decide whether:

a) the proposed project can be accepted, with or without conditions, or

b) the proposed project is opposed due to significant effects on the environment.

In its ruling the Planning Agency shall explain its main premises and conclusions and what conditions it has set, together with a description of the principal mitigating measures, where appropriate.

13. *Presentation of the Ruling*. The ruling by the Planning Agency shall be advertised in the same manner as the EIA study within a week from the date of ruling.
14. *Appeal [week 13–16]*. Anyone can appeal (in writing) the ruling of the Planning Agency to the Minister for the Environment within four weeks from the ruling.

15. *Ruling by the Minister for the Environment [week 17–24]*. The minister shall issue a reasoned ruling within 8 weeks from the expiry of the time limit for complaints.

According to time frame set by the EIA Act, the final ruling of the minister for the environment on if a project is subject to EIA study should be no longer than 12 weeks after the project is notified to the Planning Agency. The final ruling of the minister for the environment if a project has acceptable environmental impact should be within 24 weeks from the time when the EIA study is received by the Planning Agency. Any delay in response from the developer may result in subsequent delay in the overall process.

In practice, this time frame has often been significantly longer in the previous years. It may take the developer longer to respond to opinions, especially if additional research or planning is required, but the most common cause of delay is associated with the rulings of the ministry for the environment itself. Changes to the current EIA Act have been proposed, mainly to make the Act more in line with equivalent European Union legal frame but the extent of these changes and when the new Act will occur has not been presented.

14.2 The Application of Environmental Impact Assessment

Since the first EIA Act was introduced in 1994, the Planning Agency has evaluated eleven research drilling projects and eight geothermal power plant projects, both new power plants and extensions of older plants. An assessment of a power plant includes power plant structures, pipelines, wells, road connections etc. and are according to the current Act 106/2000 always subject to EIA.

Since 1994, 11 research-drilling projects have been notified to the Planning Agency, 9 of them since 2000 (subject to the current EIA Act). Seven projects were decided not to be subject to an EIA study, 6 were decided by the Planning Agency but one project after a ruling by the minister for the environment. Four projects were decided to be subject to an EIA study. One of them was accepted, one declined, one is pending on a ruling from the minister for the environment and the forth project was put on hold after being ruled to be subject to EIA study.

The most common cause for research drilling projects to be ruled as a subject to EIA is the permanent impact of roads, drilling platforms etc. in areas protected by special nature conservation Acts. This includes modern lava but all lava less than 10,000 years old (approximately 7% of Iceland) is defined as modern lava.

No single well drilling project in an operating geothermal field in Iceland, such as Krafla, Nesjavellir or Reykjanes, has ever been ruled to be subject to EIA.

14.2.1 Main Impacts and Countermeasures of Geothermal Drilling

As the current EIA Act has been in practices for less than 3 years, the application is still developing. A brief description of the main environmental impact factors and countermeasures conventionally assessed in drilling EIA are listed in table 26.

Table 26. *Environmental effects of research drilling; impact and counter-measures.*

Project factors	Environmental Impact	Counter-measurements
Civil works; roads, drill site, mining, camps etc.	May impact areas of protective importance, such as lava or wetlands; have noise or visual disturbance etc.	All sites designed to fit in with landscape, future use or to be removed later. Constructions timing may be adjusted.
Drilling fluid supply	River, lake or groundwater wells.	
Drill fluid disposal	May affect sensitive vegetation or landscape.	Normally in a nearby surface fracture; if possible in the official fluid disposal system (surface fracture, river, lake or re-injection).
Drill cuttings disposal	Metamorphic minerals have different colour than the landscape.	Buried in nearby pits.
Chemicals for drilling	May pollute sensitive environment.	Controlled and disposed with special waste after use.
Waste disposal		Waste is controlled and transported for disposal at an official and accepted site.
Environmental factors	**Environmental Impact**	**Counter-measurements**
Geothermal reservoir (unlikely)	Localised cooling by drilling fluid. Minimal reservoir pressure decrease.	This is very unlikely but if a reasoned doubt, pressure in nearby wells is specially monitored.
Geological formations and landscape	Permanent or lasting damage to special geological features and formations, such as hot springs, lava etc. or an impact on wider landscape.	Location of roads, drill sites, mining pits, camps and other construction sites is consulted with specialists to make them as little outstanding in the landscape as possible and to avoid special features.
Flora and vegetation	Possible damage to rare species or species with a risk of extinction, wetlands and other areas of special preservation value.	Change of location. Planting or re-planting.
Wildlife	Possible disturbance to rare species or species with a risk of extinction.	Timing of construction, limitation of traffic *.
Hot spring micro-organism	Possible damage to rare or species with a risk of extinction.	Has up to date not been an issue.
Visual and noise effects	Civil works construction, drilling and the associated traffic may possibly disturb tourists or rare species of animals (e.g. during breading periods).	Timing of project. Limited traffic *.
Planning and utilisation	Zoning plans may have to change.	
Community	In general, research drilling project are not likely to have a significant (negative) impact on the community.	
Transportation	Some traffic of construction equipment and drilling staff is unavoidable.	
Tourism and outdoor activities	See “visual and noise effects”.	
Archaeological and historic sites		Sites of archaeological and historical significance are avoided as possible.

14.3 Summary

The process of environmental impact assessment has been described in this chapter. The IDDP drilling program has to be notified to the Planning Agency according to Article 6 in the current EIA Act 106/2000.

In the light of the past experience of EIA for geothermal research drilling in Iceland, the associated civil construction works (roads, drill sites, camps and water supply) is the main issue of concern. If the IDDP wells are located in an operating geothermal field, such as Krafla, Nesjavellir, Svartsengi or Reykjanes, the impact of civil works will be minimal. Therefore, it is unlikely that the drilling phase of the IDDP wells will be subject to EIA study.

In the notification to the Planning Agency, the main emphasis should be on the uncertainty of the chemical composition of the produced fluid and disposal method. Conventional surface disposal may not be acceptable and alternatives have to be considered. Of the three locations most likely for this study, only Krafla power plant has a reliable re-injection system. However, it has to be addressed that only a small volume of liquid fluid is expected from the IDDP well tests and it may be possible to collect the liquid in tanks and transport it to more suitable disposal location.

15 TIME AND COST ESTIMATES

Basis of cost estimate

In order to evaluate several alternatives a spreadsheet was made to calculate the project cost, based on an estimation of the number of days the job would take. Historic data presented in this report for drilling in Iceland and for coring in Hawaii is used for this, where appropriate. From the time estimate and the per diem cost of drilling equipment, rig crews, and other time related items the cost was added up. The costs are itemized in 40 parts and added up for three phases of the project:

- Drilling. This includes all drilling related costs for conventional rotary drilling and reaming. Scientific services as outlined in the report are also included.
- Coring is for the cost of the large rig and coring unit for the period of coring and installing the technical casing. Scientific services as outlined in the report, such as for core handling, are also included.
- Logging and testing is time spent on making the conventional geophysical logs, CBL logs for cement and a multitude of temperature and pressure logs.
- The daily operating cost of the rig including overhead turned out to be around $33,000 while drilling and $36,000 while coring.

The major cost item is rig rental, for drilling and add-on for coring. The day rates for such services are somewhat fluctuating and were assumed for a top drive rig, of the kind not currently available in the country, to be $15,000/day while drilling and $12,000 while partly idle due to coring. The high rig mobilization/demobilization cost for both the top drive rig and coring unit is due to of shipping into the country. The high BOP cost is based on rental rates from an overseas source.

Then the depth related costs for casing material, mud, cement and other consumables was added up. The cost of logging, scientific and engineering services is based on current prices in Iceland.

The material costs are based on recent market prices. They may change due to market conditions and the plummeting value of the US dollar since January 1. 2002 of 21% against the Euro and 34% against the Icelandic krona. The casing fob price at the time of estimation was around 900 $/tonne. All prices are exclusive of Icelandic value added tax (VAT) now 24,5%.

IDDP cost and time estimates. Summary

This table shows the results for the two main types of IDDP wells (A large dia, B small dia), and also for "the wells of opportunity" described in the next chapter. It summarizes the cost and time of each type of well, broken down into drilling, coring and testing. The last box shows what the cost of the well B would be if no cores were taken. A contingency of 10% is applied to arrive at the total project cost.

Table 27. *IDDP cost and time summary. Cost is ex. VAT.*

	IDDP type B		**IDDP type A**		**KJ-18 (4000 m)**		**RN-12**		**Well B - No core**	
	Cost $	**Time**	**Cost $**	**Time**	**Cost $**	**Time**	**Cost $**	**Time**	**Cost $**	**Time**
Drilling	6.459.300	98	7.558.090	112	1.334.296	21	3.074.170	45	7.575.400	133
Coring	5.942.520	140	5.942.520	140	3.591.130	91	5.942.520	140	0	0
Logging, testing	712.000	20	641.500	18	350.900	12	571.000	16	273.570	11
TOTAL Base Est.	13.113.820	**258**	14.142.110	**270**	5.276.326	**124**	9.587.690	**201**	7.848.970	**144**
Contingency 10%	1.311.382		1.414.211		527.633		958.769		784.897	
TOTAL	**14.425.202**		**15.513.597**		**5.803.959**		**10.546.459**		**8.633.867**	

Spreadsheet for IDDP well B

This chapter shows a part of the cost and time spreadsheet for well type B. Table 28 shows the main inputs for the varios scenarios. The results are displayed in the bottom box as "IDDP project cost and time estimate. Below this there are two layers that contains the unit cost data. In layer 2, shown in Table 29, the cost is broken down into 40 items. The detail material costs are in layer 3, and are not shown. The drilling progress curve is shown in the Figure 40.

Table 28. *Time and cost estimate, well B to 5000 m. Cost is ex. VAT.*

Inputs (shaded gray):

	Depth (m)	Duration	ROP (m/day)
Rig move		7,0 days	
Drill 26" hole			
22-1/2" casing			
Drill 21" hole	to 350 m	7,0 days	50,0 m/day
18-5/8" casing		5,0 days	
Drill 17-1/2" hole	to 950 m	10,0 days	60,0 m/day
16" casing		7,0 days	
Drill 14-3/4" hole	to 2400 m	25,0 days	58,0 m/day
10-3/4" casing		9,0 days	
Technical casing 5" installed	to 2400 m	4,0 days	
Coring I	to 3500 m	50,0 days	22,0 m/day
Injection and stimulation		1,0 days	
Technical casing out of hole		4,0 days	
Drill 9-5/8"	to 3500 m	18,0 days	61,1 m/day
7-5/8" casing		7,0 days	
Technical casing 5" installed	to 3500 m	5,0 days	
Coring II	to 5000 m	75,0 days	20,0 m/day
Injection and stimulation		3,0 days	
Technical casing out of hole		2,0 days	
Drilling 6-1/2"			
5" casing			
Coring III			
Injection and stimulation			
Well TD	to 5000 m		
Logging (see table)		16,2 days	
Tests after tech. csg. out			
Rig down		3,0 days	
TOTAL:		**258,2 days**	

IDDP project cost and time estimate:

Drilling	$ 6.459.300	98,0 days
Coring	$ 5.942.520	140,0 days
Logging and testing	$ 712.000	20,2 days
TOTAL Base Estimate	**$13.113.820**	258,2 days
Contingency 10%	$ 1.311.382	
TOTAL with contingency	**$14.425.202**	

Daily operational cost	$ 33.366	Drilling
incl. overhead:	$ 36.743	Coring

Table 29. *Cost spreadsheet, well B to 5000 m. Level 2 to table 28. Cost is ex. VAT.*

Item nr.	DESCRIPTION	Drilling ($/unit)	Coring ($/unit)	Logging Testing ($/unit)	Drilling 98,0 days 2400 m	Coring 140,0 days 2600 m	Logging Testing 20,2 days	Total 258,2 days ($)
TIME DEPENDENT ($/day)								
1	Rig Rate, rotary rig with top drive	15.000	12.000	12.000	1.470.000	1.680.000	242.400	3.392.400
2	BOP rental + H_2S alarms	2.500	5.000	5.000	245.000	700.000	101.000	1.046.000
3	Mud motors and surveys	80.000			80.000			80.000
4	Cementing equipment	500	500		49.000	70.000		119.000
5	Coring unit with crew - drilling		6.500			910.000		910.000
6	Coring unit with crew - standby			4.800			97.000	97.000
7	Coring unit without crew - standby, 30d			1.200		36.000	24.200	60.200
8	Field lab, rental, running cost	150	150	150	14.700	21.000	3.000	38.700
9	Drilling Engineer	1.100	1.100	1.100	107.800	154.000	22.200	284.000
10	Mud logging (geologist)	900	1.000	1.000	88.200	140.000	20.200	248.400
11	Mud engineer	900			88.200			88.200
12	Logging truck and crew	1.500		2.000	147.000		40.400	187.400
13	Lodging, Catering (camp+food)	2.200	2.900	2.900	215.600	406.000	58.600	680.200
14	Rental tools	2.000			196.000			196.000
15	Water	500	500	500	49.000	70.000	10.100	129.100
16	Fuel	1.500	600	600	147.000	84.000	12.100	243.100
	TOTAL				**2.897.500**	**4.271.000**	**631.200**	**7.799.700**
DEPTH DEPENDENT ($)								
17	Logging (depth charge)	att. table:			81.100	42.020		123.000
18	Drilling mud & solids control	att. table:			78.000			78.000
19	HT Cement	att. table:			146.000			146.000
20	Bits	att. table:			268.000			268.000
21	Casing and accessories	att. table:			968.300	241.500		1.209.800
	TOTAL				**1.541.400**	**283.520**		**1.824.800**
FIXED COSTS ($)								
22	Licences, EIA	50.000			50.000			50.000
23	Well planning	70.000	30.000		70.000	30.000		100.000
24	Contracting	40.000			40.000			40.000
25	Site preparation + water supply	200.000			200.000			200.000
26	Pre-drilling 70 m (conductor)	250.000			250.000			250.000
27	Rig mob/demob	400.000	280.000		400.000	280.000		680.000
28	IDDP Science Team off site activites	100.000	200.000		100.000	200.000		300.000
29	Welding services and other	50.000	5.000		50.000	5.000		55.000
30	Drillstem inspection	120.000			120.000			120.000
31	Wellhead	att table:			268.000			268.000
32	Insurance, other than rig	100.000			100.000			100.000
	TOTAL				**1.648.000**	**515.000**		**2.163.000**
IDDP SCIENCE ($/day)								
33	Principal Iinvestigator - Proj. Mgmt.	1.100	1.100	1.100	107.800	154.000	22.220	284.020
34	Data curator	900	1.000	1.000	88.200	140.000	20.200	248.400
35	Geologists, assistants for core handl.	900	3.000	1.000	88.200	420.000	20.200	528.400
36	Core scanner and Geo Tech		100			19.000		19.000
37	Field lab, core handling, store	500	500	500	49.000	70.000	10.100	129.100
38	Telecommunications	100	100	100	9.800	14.000	2.020	25.820
39	Information handling, computers	100	200	100	9.800	28.000	2.020	39.820
40	Mscel. field office expenses	200	200	200	19.600	28.000	4.040	51.640
	TOTAL				**372.400**	**873.000**	**80.800**	**1.326.200**
	SUB TOTAL				**6.459.300**	**5.942.520**	**712.000**	
	PROJECT TOTAL							**$ 13.113.700**

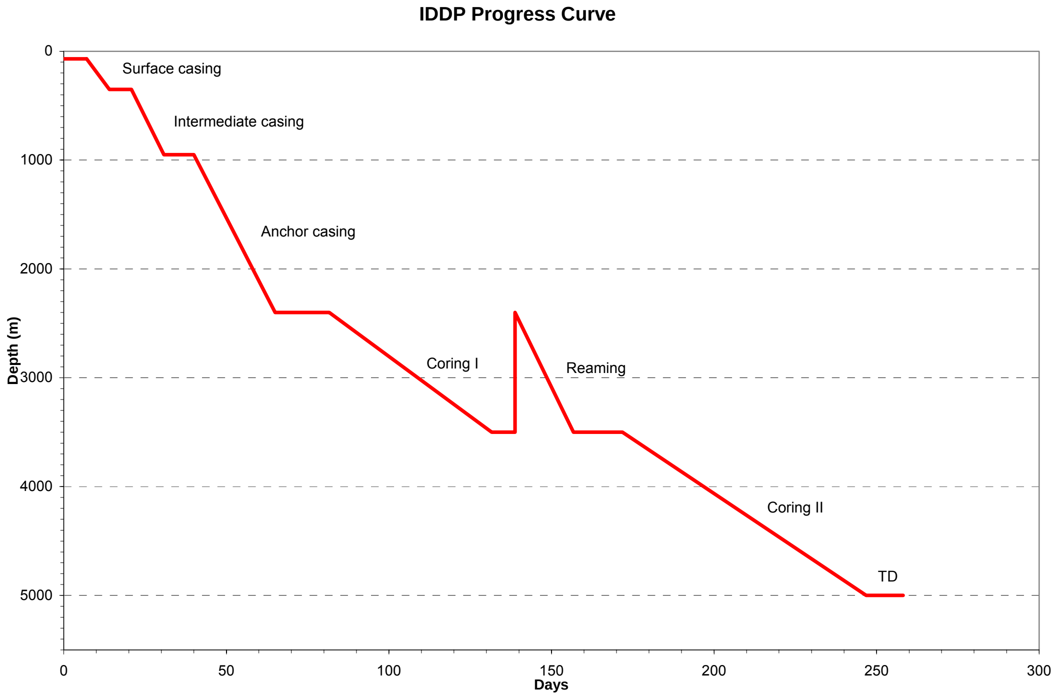


Figure 39. *Time estimate for drilling well B. Drilling progress curve.*

16 ALTERNATIVES – CORING FROM EXISTING WELLS

The high projected cost of the IDDP wells proper has been of obvious concern to both Deep Vision and SAGA. An obvious alternative option of entering an existing well and drill or core to a greater depth has been considered. At workshop No.2, this option was defined as a “pilot hole” or “well of opportunity” since it would be testing coring and sampling technology in the active tensional regimes in pressure-temperature zones defined as being of highest scientific interest. The option has a cost advantage since much of the large diameter drilling and casing would already be available. In each of the geothermal systems being considered there are wells that would potentially fulfill the role of a “well of opportunity”. In some cases also, these wells of opportunity, could either be considered as -, or be deepened by reaming, casing, and further coring to become a full scale IDDP wells.

Table 30. *Wells of opportunity discussed during WS II.*

FIELD	WELL	DEPTH (m)	TEMP (°C)	CASING	COMMENTS
REYKJANES	11	2247	320	13-3/8 ~800 m 12-1/4 open	Main feed @ 2200 m
	10	2050	320	9-5/8 liner	
NESJAVELLIR	13,16,19	1400-2265	325 @ 1500	9-5/8 to 800 8-1/2 open w/ 7 liner	All producing
	11	2265	>380		
	12		325 @ 1500		Not on production Too far from plant
TROLLADYNGA	TR-1	2308	325	13-3/8 to 750 9-5/8 liner to TD	1000-1600 entries Poor producer
KRAFLA	6	2200	300		Damage @ 1200
	18	2280	278	9-5/8 to 800 8-1/2 open to TD	no permeability
	25			9-5/8 to 1100	fish @ 1100 2000 entry pH 2-4 above magma chamber
	26				on injection
	23	2000	240	9-5/8 tp 600 8-1/2 open to 2000	
NAMAFJALL	4	1130	270		erupted tephra in 1977 open to 600

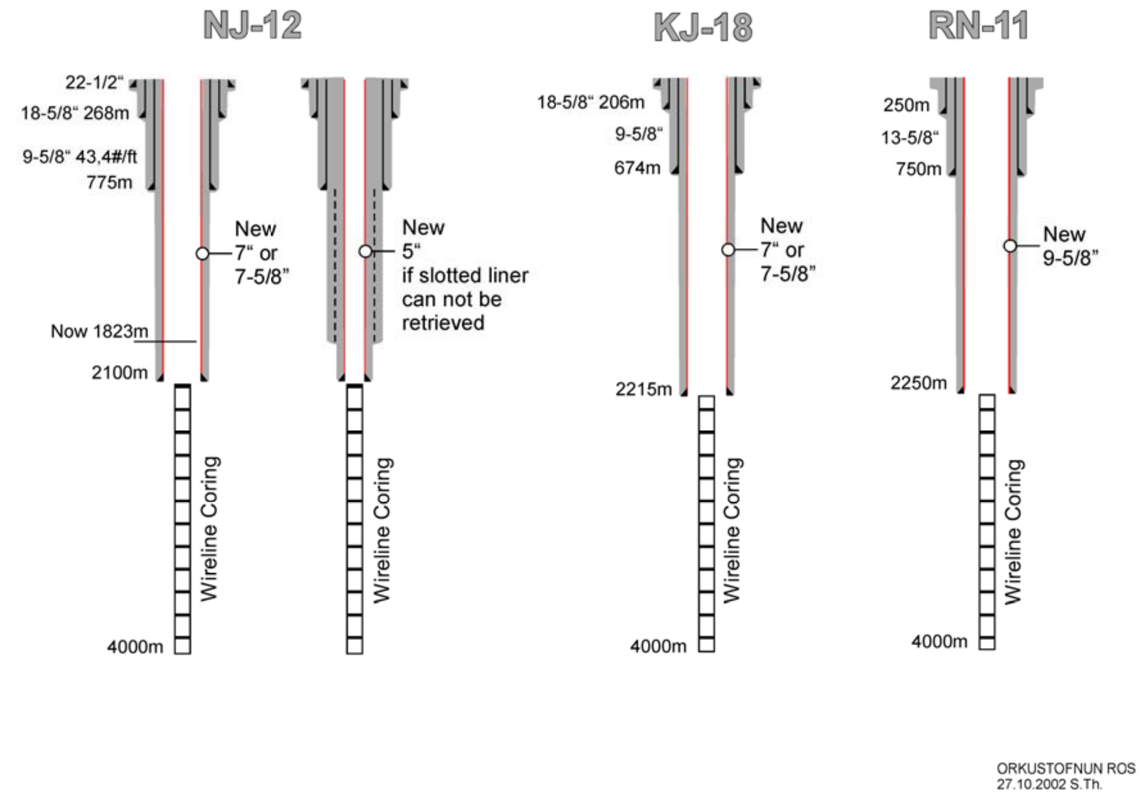


Figure 40. *Profiles of existing wells after being cored to 4000 m.*

Several recommendations were made by the meeting of the SAGA group at the conclusion of the Workshop 2:

1) As a preliminary step, the options of drilling a pilot hole or further drilling using existing holes should be considered.
2) Any preliminary work proposed should address the key scientific and technical issues of importance to the future program of deep (> 4km) drilling
3) Such a preliminary work should be made a logical step in the development of the overall program.

The principal idea for drilling and sampling a pilot hole prior to IDDP deep drilling, was to obtain scientific information and to test technologies for later use in the hot, hostile environment of the deep boreholes that will be drilled by the IDDP. For example: During drilling, how does one know when the supercritical regime has been entered? Will the entrance be signaled by a given set of high-T mineral assemblage; be detected by some mixing of gas into the drilling fluid; detected by some down-hole temperature MWD-tool; or by a combination of these or other indicators? The current thinking is that the optimum strategy would be to core-drill the IDDP holes in two steps: (1) 2.4–3.5 km - followed by reaming and cemented casing, and (2) from 3.5–5 km. Obviously, better knowledge of when to complete step 1 and move to step 2 is of primary concern, as the chief purpose of this two-step program is to separate sub-critical conventional hydrothermal fluid from the super-critical fluid of interest to IDDP. In addition to this, during both the drilling steps, injection test and tracer tests could and should be done. Some of the deep IDDP wells may in the future be used for reinjection in order to enhance the performance of the overlying fractured geothermal systems at subcritical temperatures. Therefore, injection, and tracer tests should be added to the science plan of the wells of opportunities, and evidently testing of hydrofracturing and other permeability enhancements as necessary, and even experiments on creating down-hole heat exchangers should be added too.

In conclusion, the wells of opportunities involve both scientific and technical merits as a preparatory step to IDDP, apart from the cost benefit. Clearly, as we are discussing somewhat different approach to reach the primary goal of IDDP, an explanation need be made on how this idea of wells of opportunities came by. In presentations from the feasibility study group at workshop 2, the idea was brought forward that some wells, like RN-11 at Reykjanes, might possibly serve as a proper IDDP well. There, only a casing of the right width needed be installed in the existing well, which could subsequently be deepened by core drilling. In such a case, half of the IDDP wells had already been drilled, and financing of the latter half needed to be added. Evidently, a well like this is indifferent from an IDDP well. However, the workshop, took the discussion a bit further and invented the term “well of opportunities” and considered a series of wells for the same purpose, as listed in Table 30. Still, only some of the wells listed could serve as full scale IDDP wells, as discussed below. Maps showing the well locations, and discussion on some of the wells of opportunities is dealt with in Part I of the feasibility report, to some extent (e.g. in section 10.6 and elsewhere). Part of that discussion is repeated below.

After workshop II , the Orkustofnun team working on the feasibility report, in addition to those attending the workshop, quickly reviewed all available well data on the wells of opportunities. For a variety of reasons, some of the wells listed were immediately eliminated from the list. Some were permanently damaged, others had experienced technical problems and were not considered feasible for re-entry; and some were in use as production- or reinjection wells. Soon the discussion focused on 5 options for further consideration. Two options were considered for Nesjavellir, firstly a deepening of well NJ-12 in Kyrdalur, and secondly, a new drilling of an inclined well nearby the NJ-12 drillsite. At Krafla, in NE-Iceland, one option remained for serious consideration, i.e. well KJ-18 furthest to the east in the drill field. At the Reykjanes peninsula, in SW-Iceland, two options for wells of opportunities were considered realistic, one at Reykjanes itself by well RN-11 as already mentioned, and the other in a different field further inland at Trölladyngja, well TR-01. Since this evaluation by the Orkustofnun team, a new well, RN-12, has been drilled at Reykjanes. It is close to well RN-11, which is 2248 m deep, whereas the new well RN-12 is 2500 m deep, and the deepest high-T well in Iceland to date. Both the RN-wells are 12 ¼" wide production wells, and neither of them have a slotted liner inserted.

The Orkustofnun team did not conclude by selecting "the well of opportunity". Much depends on the general condition of the wells considered, and not the less on the willingness of the energy companies to make the wells available to IDDP. That topic needs be addressed by the energy company concerned prior to a selection of "the well". It should be mentioned before continuing, that the wells considered vary in three fundamental properties. The production parts of the Krafla KJ-18 well, and the Nesjavellir NJ-12 well, were both drilled by an 8 ½" drill bit, whereas the RN-wells and the TR-01 well were drilled by a 12 ¼" bit to the bottom. Only KJ-18, RN-11 and RN-12 are without a liner, the others have liners inserted, which may or may not be retrievable?

As discussed closer in Part 1 of the feasibility report on site selection, once Deep Vision decides on what type of IDDP well to drill and where to drill it, a detailed evaluation of the field in which the target-well is situated should be undertaken, and a detailed cost estimate made. Now, only preliminary cost estimates are made for some of the options for well of opportunities discussed above, and below.

Reykjanes

The two wells considered at Reykjanes as a well of opportunities, do have the IDDP well profile of a type-B well. As such they need be classified as IDDP-wells proper. Core drilling in either well, in one or two steps, from 2,5 to 4 or 5 km, is readily attainable, once a 10 3/4" casing ha been inserted and cemented. Subsequently, "the pipe" for fluid handling and evaluation (FHE) can be inserted and tested, and this well of opportunity would not be different from a proper IDDP well. Accordingly it needs not be discussed further as a well of opportunity, but should rather be discussed as the first coring-step in sinking an IDDP well at Reykjanes. If available, well RN-12 is of higher preference as an IDDP well, as discussed in Part I of the feasibility report on well siting.

Nesjavellir

One of the key interest of IDDP is to access the high pressure, high temperature zone at Nesjavellir, as discussed in Part 1 of this report. Mainly because of the high pressure (P) at shallow depth in the center of the up-flow zone as experienced by well No.11, but also due to environmental and geographical restrictions on the west side of the Nesjavellir valley, siting an IDDP well there is literally out of the question until more is known about the center of the up-flow zone. However, sidetracking by drilling from either side seem quite possible for physical reasons, which mostly hinges on the minimum pressure head attainable within the well at each depth. A cemented safety casing to about 2,4 km is needed to enter P-T at or above the critical point, in order to control the well safely.

Well No.12 in the Kyrdalur valley, at about 150 m higher elevation than well No.11 in the Nesjavellir valley, probably represents the best suited location to attempt re-entry of the superhot zone NJ-11 encountered at Nesjavellir. The additional pressure head of 10–15 bar, makes Kyrdalur valley is favourable for well control. Accordingly, well No.12 was listed as one of the options to consider as a “well of opportunity”. It coincides with one of the most favourable sites for a full scale IDDP well, as discussed to extent in Part 1 of the report, and the IDDP site of highest priority.

Well NJ-12 was drilled by 8 ½” bit to 1823 m depth, with a 9 5/8” cemented production casing to 775 m depth. A 7 7/8” slotted liner hangs in the well at present, possibly retrievable. However, due to the liner and doubts on its retrievability, and high pressures expected at relatively shallow depths when the main upflow zone across the eruptive fissure is entered, the option of drilling a new well adjacent to NJ-12 was also considered. The benefit of a new well, inclined or straight, first and foremost is a safety concern, as wider casing design program would be applied in the case of a new well. The cost benefit of a new well as compared to an entry of NJ-12 is small, and evidently it is just a matter of taste whether a new well at NJ-12 should be classified as a “well of opportunity” or a proper IDDP well. A new inclined well near NJ-12, targeted to encounter a supercritical fluid at 3–4 km depth, would be the shallowest target available in Iceland, and no different from a high priority IDDP site discussed in Part I of this report on geosciences and well siting.

Krafla

The exploration well KJ-18 in Krafla was drilled in the late seventies as a potential production well for the Krafla Power Station. Its primary goal was a step towards defining the outer boundaries of the potential production field. It is located in the southeast side of the Krafla Volcano (see Fig. 28 in Part 1) and farthest to east of the wells in the current production field.

The well was drilled with an 8-½” bit to 2215 m. Production casing 9-5/8” was set at 674 m depth but as the well was almost without a circulation loss (only few l/s) it was left open without a liner. This makes it quite attractive for pilot coring beside the fact that the well is not being used at all. The next logical drilling program would involve setting 7-5/8” casing to 2200 m, cementing and then pilot coring to 4000 m. A deepening of 200 m prior to this casing was also considered. Either which way, the next step after casing would be to insert a 5” retrievable casing to support the DOSECC drill string during coring. This casing method has the advantage, in case of problems during coring, that the 5” casing can be removed, the problem area then bypassed by reaming, followed by a new 5–7” casing, and then coring could continue. Nevertheless, in making well KJ-18 a particularily attractive well of opportunity, the most cost beneficiary approach would be to insert a 5” casing straight away, cement it in, and bring the DOSSECC rig into the field for a single step coring to 4 km. A preliminary cost estimate for this approach is made in this report. It is justified by the expected lithology in KJ-18 at 2–4 km depth. The rock formation is considered to be fairly stable and easily drillable - that of an intrusive rock complex. The intrusive rocks are most likely of basaltic composition, dolerite dykes and gabbro, while harder acid intrusion (granophyre/granite) may occur, but subordinate in abundance. The probability of facing irretrievable problems during coring is thus considered low and the approach of a single step coring is recommended.

It should be noted that FHE-pipe cannot be installed in this type of a well, even though a 7 5/8” casing program was used, and the same applies to the NJ-12 well at Nesjavellir. Therefore, the well KJ-18 would need to be flow tested the conventional way. A series of injection tests, tracer test, test of hydrofracturing etc., could still be added to a 4 km deep KJ-18 well, in order to enhance the performance of the geothermal system.

Main technical concerns involving wells of opportunity

Assuming some or all the wells of opportunities be considered further, some consideration of technical nature need be added. Here, a case example is made of well KJ-18.

- Casing and well construction: The existing casings and wellhead equipment has to be inspected and the casing be deep enough to allow deep further drilling.
- Access: Well KJ-18 is relatively high up in the hills of the Karla Volcano where winter conditions are severe. Winter conditions may set as early as mid- September, and leave as late as May. During the access window for 3 ½– 4 summer months, roads may have to be repaired or even changed to allow secure access throughout the duration of the well intervention.

Good facilities for drilling and research crews are available at the Krafla Geothermal Power Station. This includes camp, canteen, storage facilities and a small workshop. Well KJ-18 is located approximately at approximately 10 minutes driving distance from the Krafla Power Station.

Other sites (Trölladyngja, Hengill, Námafjall)

Other sites for wells of opportunities have been considered. Of these, only well TR-01, in the Trölladyngja field at the Reykjanes Peninsula, need be considered further. The well was drilled to 2300 m depth in the year 2000, and has a hanging 9 5/8” liner to target depth, possibly retrievable. The bottom hole temperature is 325°C, and the lowermost 500 m of the well show a thermal gradient of about 100°C/km. Assuming similar gradient for the next km or so, and a dry well, ~ 400°C should be met at 3 km. A dolerite/gabbro intrusion was met at the bottom of the well, but otherwise intrusive rock intensity was not high. As such, the well might possibly serve as an IDDP pilot hole for research. And, as the casing design is according to well design B of this report, the well might even be reamed, cased and deepened to become a full blown IDDP well. The fluid composition is dilute, slightly more saline than Nesjavellir, but far below the Reykjanes wells in salinity.

The fact that well TR-01 is the first hole sunk in the Trölladyngja well field, is the greatest disadvantage of the well be considered as a well of opportunity. For instance, a conceptual geothermal model of the area is lacking and the well appears to be marginal to the main hydrothermal field. More wells are expected to be drilled at Trölladyngja field in the near future, inevitably adding more data to the field. Therefore, the TR-01 well is ranked low in priority as compared to other options, but it may well become an attractive option within a few years.

17 RISK ASESSMENT AND IMPACT

The proposed IDDP research well will be the deepest well to be drilled in Iceland and the target zone fluid is expected to be of higher pressure and temperature than previously experienced in any Icelandic geothermal project. It will be the hottest 5000 m deep well in the world. It will also be the world´s first well to be drilled with the purpose of exploring fluid above critical pressure and temperature.

Table 31. *Ranking of drilling risks. Impacts and actions.*

Item	Description/Impact	Risk	Action
Special drilling risks			
Water supply failure	Can cause loss in well control	L	Spare water pumps, water storage tanks
Rig equipment failure	Drilling operation stops	L	Strict inspection requirements, spare part
Drillstring failure	Drilling operation stops	L	Strict inspection, fish back string
Casing failure	Drilling operation stops	L	Strict inspection, fish back casing, plug and side track if fishing not possible
Cement failure	Drilling operation stops	L	Cement from top, penetrate casing and re-cement
Wellbore failure	Drilling operation stops	H	Cement plugs, intermediate casing numbers
Formation fracturing	E.g. due to too high fluid column and formation cooling	M	Fracture tests to avoid; cement plugs and re-drilling if more than 10 l/s fluid loss
Core recovery	Loss of science opportunities	M	Stop coring, spot coring and conventional drilling
Underground pressure blow-out		H	To avoid, cold drilling fluid to the well at ALL times. If occurs, BOPs close, heavy drilling fluid (mud) injected through kill line – if not possible to control well, killed with heavy mud or earth
High temperature	Affects material function, risks well control	H	Alternate material selection, increase cooling
Acid formation fluid	Can corrode casing and drilling equipment	M	Equipment and material selection
Risk of nature			
Sever weather conditions	Strong wind, snow etc will delay drilling operations	M	Avoid operations during the worst weather-months
Volcanic eruptions	Ash deposits, access difficulties,	L	Monitor geological activity
Earthquakes	Well collapse, mast collapse, water supply failure etc.	L	Monitor geological activity
Special cost risks			
Low rate of penetration	Delay in drilling operation will increase cost of rig, science team, camp operation etc.	H	Alternate mud motor, bit and/or weight on bit
Poor bit performance	Delay	M	Alternate bits, change WOB
Delays in supply equipment, material & an personnel	Delay in drilling	L	Detailed project planning

Due to the novel nature of the IDDP well, there is great uncertainty involved with most of the key factors involved with the project. Therefore, risk assessment and risk management will be central to the well planning phase. At this feasibility stage, the key risk items have been identified, their impact assessed and action plans briefly outlined. Table 31 summaries the key risk items special for drilling the IDDP in Iceland, in addition to conventional geothermal well drilling.

As can be seen in Table 31, many factors can cause a delay the drilling project which will then add to the expected project cost. The cost estimate, presented in chapter 15, includes the most likely additional cost to occur but there is still the risk of a more "catastrophic" event that may result in significant cost increase or that the well can not be completed.

18 CONCLUSIONS

- Two types of wells were designed to meet the goals set out by SAGA, mainly of different diameters. The main task was a well design that would meet the two major goals of the project; (a) allow fluid to be produced to evaluate the feasibility of its utilization for the power companies and (b) acquire scientific data by logging and continuously coring the lower part of the hole. The larger diameter hole has several advantages in terms of flexibility and later flow-testing. It is, therefore, the preferred design.

- It is concluded that the drilling portion of the project is feasible if sufficient funding is available to cover all contingencies. The total cost is estimated to be US$ 14.4–15.5 million (early 2002 dollars). A contingency of 10% is included.

- Information on comparable drilling projects were acquired and studied. It is clear that this is a novel project, especially as it constitutes deep, continuous core-drilling in hotter (super-critical) conditions than previously done.

- The cost estimate is based on unit costs for rig rate, materials, logging services and personnel. The daily operational cost of the rig and all on-site personnel is around US$ 33,000 per day while drilling, and $36,000 while coring. The time estimates are based on data from drilling in Iceland of a conventional well, and from DOSECC on expected coring rates. The estimated time for coring is 140 days; 112 days for drilling; and 18 days for logging-a total of 270 days. The greatest uncertainty is how long the project will take.

- The casing string will be deep enough to control blow-outs, and the BOP stack robust enough to take the pressure. There are, however, temperature limitations on the BOP seals. Thus cooling ports will be provided, and an ample and reliable source of cold water. A separate BOP stack is required for the coring string.

- The casing profile will be similar to a conventional large diameter geothermal well. Drilling ahead by coring and then subsequently reaming and casing will be done from 2400–3500 m, and then only coring below 3500 m. A separate hang-down casing will have to be used (a 5" "technical casing") to guide the coring equipment in the large hole.

- A hybrid coring system (DOSECC) that can be mounted inside the mast of a conventional rotary rig was selected for this study. The amount of information available on that system in terms of cost and performance were major factors in the selection. The deepest cores taken with that system to date are from 3000 m.

- During conventional drilling, the well can be cooled sufficiently to allow the use of conventional tri-cone bits for conventional rotary drilling. Much less drilling fluid is pumped during coring, and thus the cooling of the well during coring will be insignificant. This puts limitations on the selection of logging tools in the cored hole.

- Core- and data handling will be according to what is practiced in ICDP and DOSECC scientific drilling projects and the required on-site facilities provided.

- Drilling of deep high-enthalpy exploration wells in Iceland is subject to the Environmental Impact Assessment Act No 106/2000. Based on current practices of the Act, it is not considered likely that the drilling project will be subject to a full EIA study if the IDDP well site is within a current geothermal production field. However, if the project is ruled to be subject to an EIA study, it would add 6–12 months to the preparation time.

- The key technical risk factors were identified as wellbore failure, underground pressure blow-out and excessive thermal stresses in equipment and casing strings. Hence, effective cooling control is essential. Rate of drilling penetration, especially during coring, is also a key risk factor that could greatly affect the overall project cost. However, it is believed that all risk factors can be handled, and that the risk is within acceptable limits.

- Possibilities other than drilling a new well were considered, but not in detail. In this case of “wells of opportunity”, existing deep geothermal wells would be used, and thus the first 2000–2500 m would already be in place. For these wells, the casing would be set at 2500 m and the target depth for coring 4000 m. The cost estimates rage from US$ 5.8–10.5 million. The option of taking no cores, but drilling a new well to 5000 m is estimated to cost US$ 8.6 million.

IDDP

Feasibility Report

APPENDIX :

To Part II :

Casing Design

Iceland Deep Drilling Project

Casing Design

Verkfræðistofa Guðmundar og Kristjáns

May 2003

0. Summary

Introduction

The aim of this study is to design a casing program for a 5000 m deep supercritical well proposed by the Iceland Deep Drilling Project (IDDP).

Design conditions

The casing design has to withstand extreme temperature and pressure with special attention on safety. It is assumed that the temperature profile will follow saturation conditions for column of boiling water down to the critical point (CP) here assumed to be at 3500 m depth. Below the CP two temperature profiles scenarios are inspected. Firstly it is assumed that the temperature will rise linearly to 550 °C at 5000 m and secondly isochor condition which will render bottom hole temperature of 390 °C. The bottom hole pressure is assumed to be 25 MPa and 26,7 MPa respectively.

Casing programs

The result of the casing design is:

- For the materials consider for the top part of the anchor casing 2,5Cr-1Mo (SA-213 T22) is consider the best suited material for the time being. The wall thickness of the 13-3/8” anchor casing is 44 mm and for 10-3/4” 31 mm.
- Thick walled grade K55 casing with premium connections is the best suited for high temperature operation and is planed for the other part of the casing program. Premium connections with metal to metal seals and of higher grade material of quenched and temper steel containing molybdenum is considered to render adequate seal and strength.
- Successful cementing of casings is the basis for safe operation of the well and thermal cycling should be kept to minimum to enhance the lifetime of the well.

The corresponding casing program is:

	Casing outside diameter Inch	Normal weight of casing lbs/ft	Wall thickness mm	Casing Depth m	Material
Well profile A					
Surface casing	22-1/2			400	K55
Intermediate casing	18-5/8	87,5	11,05	800	K55
Anchor casing	13-3/8	68,0	44,1 / 12,19	2400	2,5Cr-1Mo / K55
Production casing	9-5/8	47,0	11,99	3500	K55
Well profile B					
Surface casing	18-5/8	87,5	11,05	400	K55
Intermediate casing	16	84,0	12,57	800	K55
Anchor casing	10-3/4	51,0	30,4 / 11,43	2400	2,5Cr-1Mo / K55
Production casing	7-5/8	33,7	10,92	3500	K55

1. Design Criteria

1.0 Introduction

The aim of this study is to design a casing program for a 5000 m deep supercritical well proposed by the Iceland Deep Drilling Project (IDDP).

Tentative casing depth is 2400 m for the anchor casing and 3500 m for the production casing. Formation critical temperature and pressure is assumed at 3500 m and the bottom hole formation temperature is assumed 400 to 550 °C at pressure of 25 to 27 MPa.

1.1 The approach

The temperature to be expected in the well is higher than in conventional geothermal wells and much higher than is experienced in the petroleum industry. The bottom hole temperature is assumed to be 550°C (1022°F) and the flowing well head temperature is estimated to be 500°C (932°F). The pressure is expected to be 25 to 27 MPa (3600 to 3900 psi) which is relatively low compared to the petroleum industry.

In the design of geothermal wells the guidelines of the petroleum industry have been followed but when the temperature exceeds 150°C (302°F) the geothermal industry have been using ASME and ASA codes as suggested in NZS 2403:1991 “the top section of the anchor casing shall also be designed to comply with the ASME B&PVC in respect of steel grade and thickness”.

In Iceland, as outlined by Karlsson 1996, the B&PVC VIII Division 2 – Alternative Rules have been used for wells with maximum temperature of less than 350°C (662°F). The temperature limit for VIII Division 2 is 700°F (371°C) for carbon steel and low alloy steel and therefore in our case VIII Division 1 should be used.

For the scope of Division 1, the pressure vessels are containers for containment of pressure, either internal or external. This pressure may be obtained from an external source, or by the application of heat from a direct or indirect source, or any combination thereof.

In Shell Made From Pipe part of Requirements for pressure vessels construction of carbon and low-alloy steel

(a) Section II, Part D provided the material of the pipe is manufactured by the open-hearth, basic oxygen, or electric furnace process.
(b) Shells of pressure vessels may be made from electric resistance welded pipe or tubing listed in Table 1A of Section II, Part D in nominal diameters up to 30 in. (762 mm) provided the material is manufactured by the open-hearth, basic oxygen, or electric furnace process.

In relation to the rules of Division 1 of Section VIII, the rules of Division 2 are more restrictive in the choice of materials which may be used but permit higher design stress intensity values to be employed in the range of temperatures over which the design stress intensity value is controlled by the ultimate strength or the yield strength and more precise design procedures are required.

Following material were investigated for this study,
three from B&PVC,

Carbon Steel, SA-106C;
Carbon – 0,5% Molybdenum, SA-209 T1a and
Chrome Steel, 2-1/4% Chrome – 1% Molybdenum, SA-213 T22

and information in the literature for

API grade J55.

The material is discussed in chapter 3..

1.2 Well Condition

In exploratory wells where temperature and pressure profiles versus depth can not be approximated from existing data or from additional investigations, values to be used for well design is based on the following assumptions

- It is assumed that subsurface temperature values will follow saturation conditions for column of boiling water (BPD) down to the critical point (CP) here assumed to be at 3500 m depth. Below the CP two temperature profile scenarios are inspected. First is assumed that the temperature will rise linearly from 374°C at the CP to 550°C at 5000 m and secondly isochor condition is assumer which will render bottom hole temperature of 390°C. The bottom hole pressure is assumed to be 25 MPa and 26,7 MPa respectively.

Temperature and pressure profiles listed in Table 1.1 is shown in Figure 1. 1 and 1.2 for static and flowing well.

TABLE 1.1 Boiling and Flowing Conditions (Bjarnason, 2002)

	Static Well			Flowing Well					
				9” pipe				4” pipe	
				550°C. 25 MPa		Isochor		550°C. 25 MPa	
Depth m	Pressure 20°C water MPa	Pressure Boiling water MPa	Tempera t. °C	Pressure MPa	Temperat. °C	Pressure MPa	Temperat. °C	Pressure MPa	Temperat. °C
0	0	0	100	19,5	499	14,52	340	16,1	436
20	0,20	0,19	132						
40	0,39	0,36	149						
60	0,59	0,55	162						
80	0,78	0,73	172						
100	0,98	0,90	180	19,6	501	14,69	341	16,3	439
150	1,47	1,33	196	19,7	501	14,78	341	16,4	441
200	1,96	1,73	208	19,7	502	14,86	342	16,5	442
250	2,45	2,18	219	19,8	503	14,95	342	16,6	444
300	2,94	2,55	227	19,8	503	15,04	343	16,7	446
350	3,43	2,96	235	19,9	504	15,13	343	16,7	447
400	3,92	3,37	242	19,9	504	15,22	344	16,8	448
450	4,41	3,75	248	20,0	505	15,31	344	16,9	450
500	4,90	4,15	254	20,0	506	15,40	345	17,0	451
600	5,87	4,91	264	20,1	507	15,58	346	17,2	454
700	6,85	5,67	273	20,2	508	15,76	347	17,4	457
800	7,83	6,42	281	20,3	509	15,95	348	17,5	460
900	8,81	7,13	288	20,5	510	16,14	349	17,7	462
1000	9,79	7,90	295	20,6	511	16,33	349	17,9	465
1200	11,70	9,24	306	20,8	514	16,72	351	18,3	470
1400	13,66	10,60	316	21,0	516	17,12	353	18,6	475
1500	14,70	11,34	321	21,1	517	17,32	354	18,8	478
1600	15,68	11,96	325	21,2	518	17,53	355	19,0	480
1800	17,64	13,27	333	21,4	520	17,95	357	19,3	485
2000	19,60	14,33	339	21,6	522	18,39	359	19,7	490
2200	21,56	15,64	346	21,8	524	18,84	361	20,0	495
2400	22,54	16,74	351	22,1	526	19,39	363	20,4	499
2500	24,50	17,26	354	22,2	527	19,54	364	20,5	502
2600	24,48	17,91	357	22,3	528	19,78	365	20,7	504
2800	27,44	18,80	361	22,5	530	20,27	367	21,1	509
3000	29,40	19,85	365	22,7	532	20,78	369	21,4	513
3200	31,36	20,70	369	22,9	534	21,31	371	21,8	518
3400	33,32	21,72	373	23,1	532	21,86	374	22,1	523
3500	34,30	22,02	374	23,2	537	22,14	375	22,3	525
4000				23,8	542	23,60	380	23,2	536
4500				24,3	546	25,12	386	24,0	544
5000				25	550	26,68	391	25,0	550

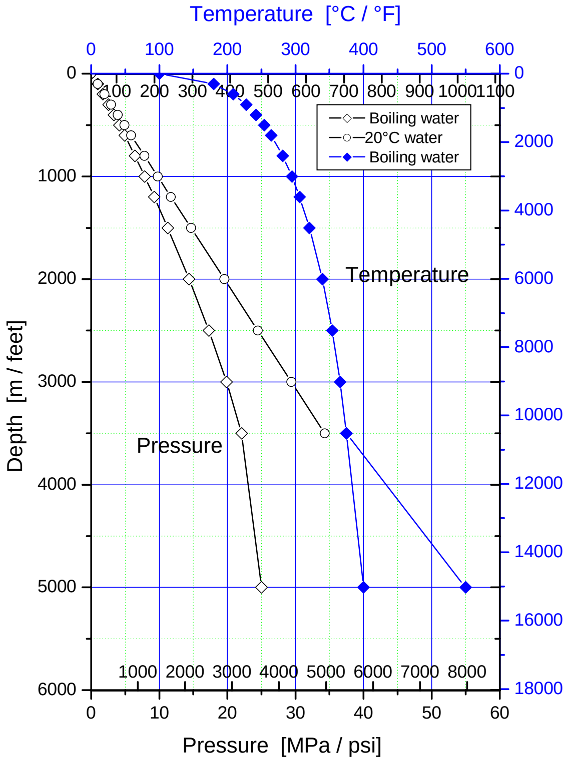


Figure 1.1 Static temperature and pressure

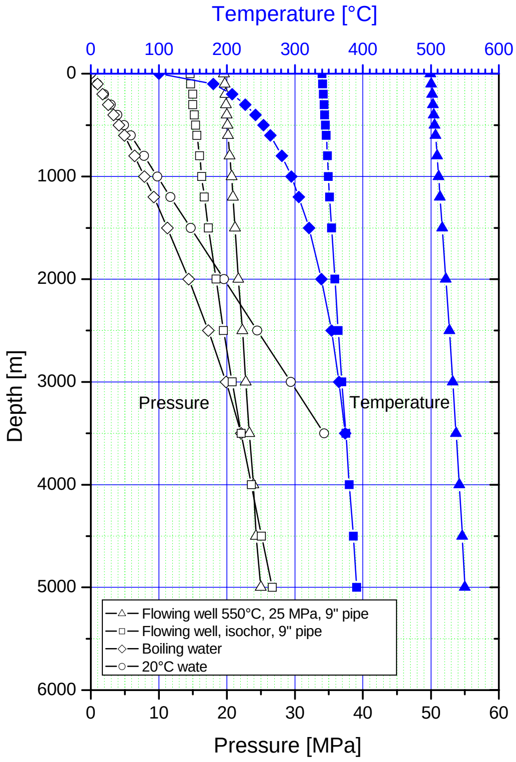


Figure 1.2 Flowing well temperature and pressure

1.3 Design Conditions

As outlined in New Zealand Code of practice for deep geothermal wells (NZS 2403:1991) it is assumed for design purposes, the fluid pressure in the well at any depth shall be greatest of:

- The saturation pressure of steam at the level of highest temperature in the open hole, less that due to column of saturated steam up to the level being considered.
- Fluid pressure in the formation at any level in open hole, less that of column of gases to the depth being considered.

And further the top section of each casing string and wellhead shall be design to withstand the following pressure and temperature conditions:

- The fluid pressure at maximum well depth less the pressure due to column of gases to the wellhead. The wellhead temperature shall be assumed to be ambient. Here the pressure at well-head is assumed to be the bottom hole pressure.
- The saturation pressure of steam at the level of maximum temperature in the open hole, less the pressure due to column of dry, saturated steam to the wellhead. The design wellhead temperature shall be the saturation temperature corresponding to design wellhead pressure.

The conditions for well profile A and B are listed in Table 1.2 and depictured in Figure 1.3

The assumption of only saturated steam is a conservative assumption since a mixture and water and steam is the usual case for most geothermal wells. In view of the uncertain circumstances the assumption is considered valid.

Table 1.2 Design Conditions

		Surface casing	Intermed. casing	Anchor casing		Production casing	
						Linear temperature profile	Isochor
Casing diameter, Vellprofile A	in	22-1/2”	18-5/8”	13-3/8”		9-5/8”	
Casing diameter, Vellprofile B-1	in	18-5/8”	16”		10-3/4”	7-5/8”	
Casing depth	m	400	800	2400		3500	
Open hole depth	m	800	2400	3500		5000	
Open hole							
Highest temperature in open hole	°C	281	351	374			
Saturation pressure at highest temperature	MPa	6,4	16,7	22,1			
Assumed highest temperature	°C					550	390
Assumed highest pressure	MPa					25,0	26,7
Wellhead							
Flowing Conditions, linear temperature profile							
Flowing pressure	MPa			19,5	18,0		
Flowing temperature	°C			499	475		
Flowing Conditions, isochor							
Flowing pressure	MPa			14,5	14,2		
Flowing temperature	°C			340	338		
Saturated steam column							
Wellhead pressure	MPa	6,1	14,0	17,7		19,7	20,9
Saturation temperature at wellhead pressure	°C	278	337	356		364	369
Empty well							
Wellhead pressure	MPa	6,4	16,7	22,1		25	26,7
Ambient temperature	°C	20	20	20		20	20

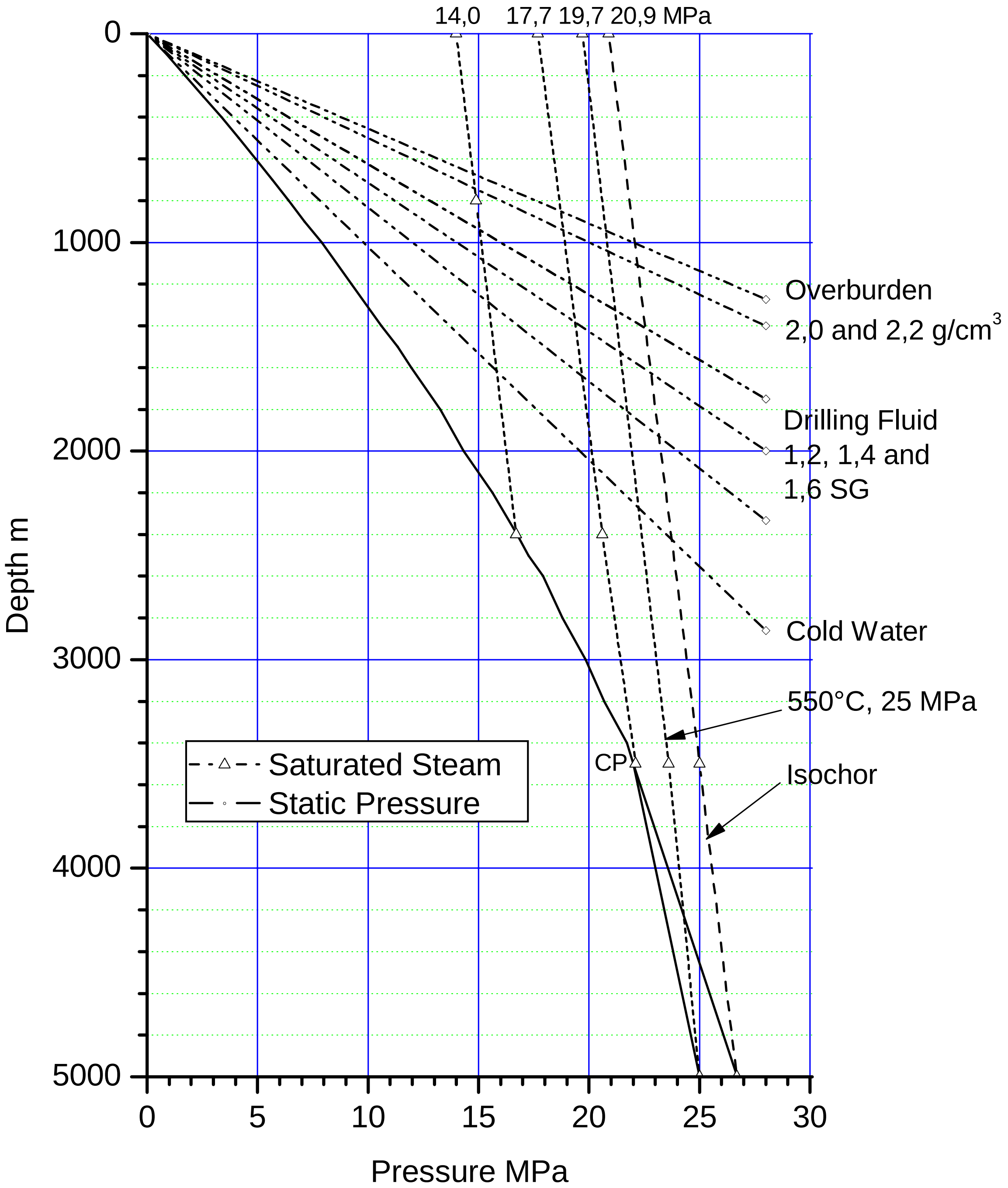


Figure 1.3 Design Conditions

2. Casing String

Well Profile (Thorhallsson 2002)

Table 2.1 Casing and bit sizes

	Casing outside diameter inc	Drill bit inc	Normal weight of casing lbs/ft	Bit size immediately below drift inc	Casing Depth m
Wellprofile A					
		26			
	22-1/2				400
		21			
	18-5/8		87,5	17-1/2	800
		17-1/2			
Anchor casing	13-3/8		68,0	12-1/4	2400
		12-1/4			
Production casing	9-5/8		47,0	8-1/2	3500
		8-1/2			
	7		26,0		3500/5000
Wellprofile B					
		21			
	18-5/8		87,5	17-1/2	400
		17-1/2			
	16		84,0	14-3/4	800
		14-3/4			
Anchor casing	10-3/4		51,0	9-5/8	2400
		8-3/4			
Production casing	7-5/8		33,7	6-5/8	3500
		6-1/2			
	5-1/2		20,0		3500/5000

3. **Materia**l

3.1 Long-time stress-rupture and/or creep

The temperature at which long-time stress-rupture and or creep will begin to control the maximum permissible operating stress has not been determined but has been estimated to be about 650 to 700°F (340 - 370°C) (Thomas 1967). Stress-rupture and creep properties estimated similar analyses and heat treatments. Here molybdenum content and, to a lesser extent, tempering appear advantageous. Standard steel with a mean of 0,3% molybdenum which has rupture properties significantly higher than the straight carbon steel.

Basis for establishing stress values in B&PVC II

The maximum allowable stress shall be the lowest value obtained from the criteria in Table 3.1 and 3.2 of B&PVC II Part D Materials.

At temperatures in the range where creep and rupture strength govern the selection of stresses, the maximum allowable stress value are not to exceed the lowest of the following:

(1) 100% of the average stress to produce a creep rate of 0,01%/1000 hr;
(2) 100 F_{avg}% of the average stress to cause rupture at the end of 100.000 hr;
(3) 80% of the minimum stress to cause rupture at the end of 100.000 hr.

Stress values for high temperature are based, whenever possible, on representative uniaxial properties of the materials obtained under standard ASTM testing conditions or equivalent. The stress values are based on properties of the materials and no consideration is given for corrosive environment, for abnormal temperature and stress conditions, or for other design conditions.

Nomenclature for Table 3.1 and 3.2:

F_{ave} = multiplier applied to average stress for rupture in 100,00 hr (11,4 y). At 1500°F (816°C) and below, $F_{ave} = 0,67$.
R_T = ratio of the average temperature dependent trend curve value of tensile strength to the room temperature tensile strength
R_Y = ratio of the average temperature dependent trend curve value of yield strength to the room temperature yield strength.
S_C = average stress to produce creep rate of 0,01%/1000 hr.
$S_{R\ ave}$ = average stress to cause rupture at the end of 100.000 hr
$S_{R\ min}$ = minimum stress to cause rupture at the end of 100.000 hr
S_T = specified minimum tensile strength at room temperature
S_Y = specified minimum yield strength at room temperature

Table 3.1

CRITERIA FOR ESTABLISHING ALLOWABLE STRESS (“S”) FOR TABLES 1A AND 1B, B&PVC II Part D - Properties

	Room Temperature and Above						
Product/Material	Tensil Strength		Yield Strength		Stress Rupture		Creep Rate
Wrought or cast ferrous and nonferrous	$S_T/3,5$	$1,1/3,5\ S_T R_T$	$2/3 S_Y$	$2/3\ S_Y R_Y$ or $0,9\ S_Y R_Y$	$F_{avg}\ S_{R\ avg}$	$0,8\ S_{R\ min}$	$1,0\ S_C$
Welded pipe or tube, ferrous and nonferrous	$0,85/3,5\ S_T$	$(1,1x0,85)/3,5\ S_T R_T$	$2/3x0,85\ S_Y$	$2/3x0,85\ S_Y R_Y$ or $(0,9x0,85)\ S_Y R_Y$	$(F_{avg}\ 0,85)\ S_{R\ avg}$	$(0,8x0,85)\ S_{R\ min}$	$0,85\ S_C$

Table 3.2

CRITERIA FOR ESTABLISHING DESIGN STRESS INTENSITY VALUES (“S_m”)FOR TABLES 2A AND 2B, B&PVC II Part D - Properties

Product/Material	Tensil Strength		Yield Strength	
Wrought or cast ferrous and nonferrous	$1/3\ S_T$	$1,1/3\ S_T R_T$	$2/3\ S_Y$	$2/3\ S_Y R_Y$ or $0,9\ S_Y R_Y$
Welded pipe or tube, ferrous and nonferrous	$0,85/3\ S_T$	$(1,1x0,85)/3\ S_T R_T$	$0,85/1,5\ S_Y$	$0,85/1,5\ S_Y R_Y$ or $(0,9x0,85)\ S_Y R_Y$

From B&PVC II Part D – Properties MATERIALS the following tables are significant for material selection

Table 1A	Section I; Section III, Class 2 and 3; and Section VIII, Division 1 Maximum Allowable Stress Values S for Ferrous Materials
Table 2A	Section III, Class 1 and Section VIII, Division 2 Design Stress Intensity Values S_m for Ferrous Materials
Table 3	Section II, Class 2 and 3; and Section VII, Division 1 and 2 Maximum Allowable Stress Values S for Bolting Materials
Table 4	Section III, Class 1 and Section VIII, Division 2 Design Stress Intensity Values S_m for Bolting Materials
Table U	Tensile Strength Values S_u for Ferrous and Nonferrous Materials
Table Y –1	Yield Strength Values S_y for Ferrous and Nonferrous Materials
Table TE-1	Thermal Expansion for Ferrous Materials
Table TM-1	Moduli of Elasticity E of Ferrous Materials for Given Temperature

TABLE 3.3 Moduli of elasticity and Thermal expansion

Temperature			Modulus of elasticity	Coefficient of thermal expansion		Poisson's Ratio
°F	°C		E x 10^6 MPa	(mm/mm/°C x 10^{-6}		
				instant	mean	
100	38		0,203	11,70	11,70	0,3
200	93		0,199	12,42	12,06	0,3
300	149		0,195	13,14	12,42	0,3
400	204		0,191	13,86	12,78	0,3
500	260		0,188	14,40	13,14	0,3
600	316		0,184	15,12	13,32	0,3
700	371		0,176	15,48	13,68	0,3
800	427		0,167	16,02	14,04	0,3
900	482		0,154	16,38	14,22	0,3
1000	538		0,141	16,74	14,58	0,3
1100	893		0,124	17,10	14,76	0,3

Following material were investigated for this study,

three from B&PVC,

- Carbon Steel, SA-106C;
- Carbon – 0,5% Molybdenum, SA-209 T1a and
- Chrome Steel, 2-1/4% Chrome – 1% Molybdenum, SA-213 T22

and

API grade J55 and K55, information in the literature.

These materials are listed in Table 3.4 and 3.5, and allowable stress values in Table 3.6. The findings for J55/K55 is depictured in Figure 3.1 and 3.2 and graphic comparisons of selected material is shown in Figure 3.3 and 3.4.

Table 3.4 Materials

Nominal Composition	Product Form	Spec No.	Type/Grade	Alloy Desig./ UNS No.	Min. Tensile Strength ksi	Max Yield Strength	Min Yield Strength ksi	Max. Temp. Limits °F VIII-1	°F VIII-2	External Pressure Chart No.
2001 ASME B&PVC, Part D- Properties, MATERIALS (2002 Addenda July 1, 2002)										
Carbon steel	Smls. Pipe	SA-106	C	K03501	70		40	1000	700	CS-2
C - 1/2Mo	Smls. Pipe	SA-209	T1a	K12023	60		32	1000	700	CS-2
2-1/4Cr - 1Mo	Smls. Pipe	SA-213	T22	K21590	60		30	1200	900	CS-2
API 5CT Specification for Casing and Tubing (Third Edition, December 1, 1990)										
Carbon steel	Smls. Pipe	J - 55			75	80	55			
Carbon steel	Smls. Pipe	K - 55			95	80	55			
USS Tubular prod. (2202)										
K - 55	Smls. Pipe	K - 55			109 - 113	71.5-72.5				

Table 3.5

	Alloy Desig./ UNS No	C	Si	Mn	Cr	S	P
Unified Numbering System for Metals and Alloys (second edition Sept 1977)							
SA-106 / C	K03501	0.35max	0.10min	0.29-1.06			0.058max
SA-209 / T1a	K12023	0.15-0.25	0.10-0.50	0.30-0.80		0.44-0.65	0.045max
SA-213 / T22	K21590	0.15 max	0.50 max	0.30-0.60	1.65-2.50	0.90-1.10	0.030 max
IJPG2000-15049 (Viswanathan and Bakker 2000)							
T22		0.12	0.3	0.45	2,25	1.0	
API 5CT Specification for Casing and Tubing (Third Edition, December 1, 1990)							
J - 55 / K - 55						0.030max	0.030max
USS Tubular prod. (2002)							
K - 55		0.34-0.37	0.24	1.37	0.03	0.12	0.013

Table 3.6 Material Strength Properties

2001 ASME Boiler & Pressure Vessel Code, II, Part D-Properties, Materials,
P.D. Thomas (1967) and Mannersmann (2002)

Materials		SA-106C		SA-209 T1a C-0,5Mo		SA-213 T22 2,25Cr-1Mo		API K55/J55		
								Mann.		Thomas
Maximum Allowable Stress Values, Table 1A		S		S		S		S		S
Design Stress Intensity Values, Table 2A			Sm		Sm		Sm			
°C	°F	ksi	ksi	ksi	ksi	ksi	ksi	ksi		ksi
20,0	68							23,6		33
37,8	100	20,0	23,3	17,1	20,0	17,1	20,0			
93,3	200	20,0	23,3	17,1	19,7	17,1	18,5			33
100,0	212							20,0		
148,9	300	20,0	23,3	17,1	18,7	16,6	18,1	19,0		
200,0	392							18,5		
204,4	400	20,0	22,9	17,1	17,9	16,6	17,9			33
250,0	482							18,1		
260,0	500	20,0	21,9	17,1	17,3	16,6	17,9			33
300,0	572							17,9		
315,6	600	20,0	19,7	17,1	16,7	16,6	17,9			33
343,3	650	19,8	19,4	17,1	16,4	16,6	17,9			
350,0	662	19,4	19,4	17,0	16,3	16,6	17,9	17,6		
371,1	700	18,3	19,2	16,8	16,1	16,6	17,9			25,5
380,0	716	17,2		16,7		16,6				
398,9	750	14,8		16,4		16,6	17,9			
410,0	770	13,7		16,2		16,6	17,9			
426,7	800	12,0		15,9		16,6	17,8			18
440,0	824	11,6		15,8		16,6				
450,0	842	9,7		15,5		16,6				
454,4	850	9,3		15,4		16,6	14,5			
482,2	900	6,7		13,7		13,6	12,8			10,5
500,0	932	5,0		10,2		11,8				
510,0	950	4,0		8,2		10,8				
537,8	1000	2,5		4,8		8,0				3

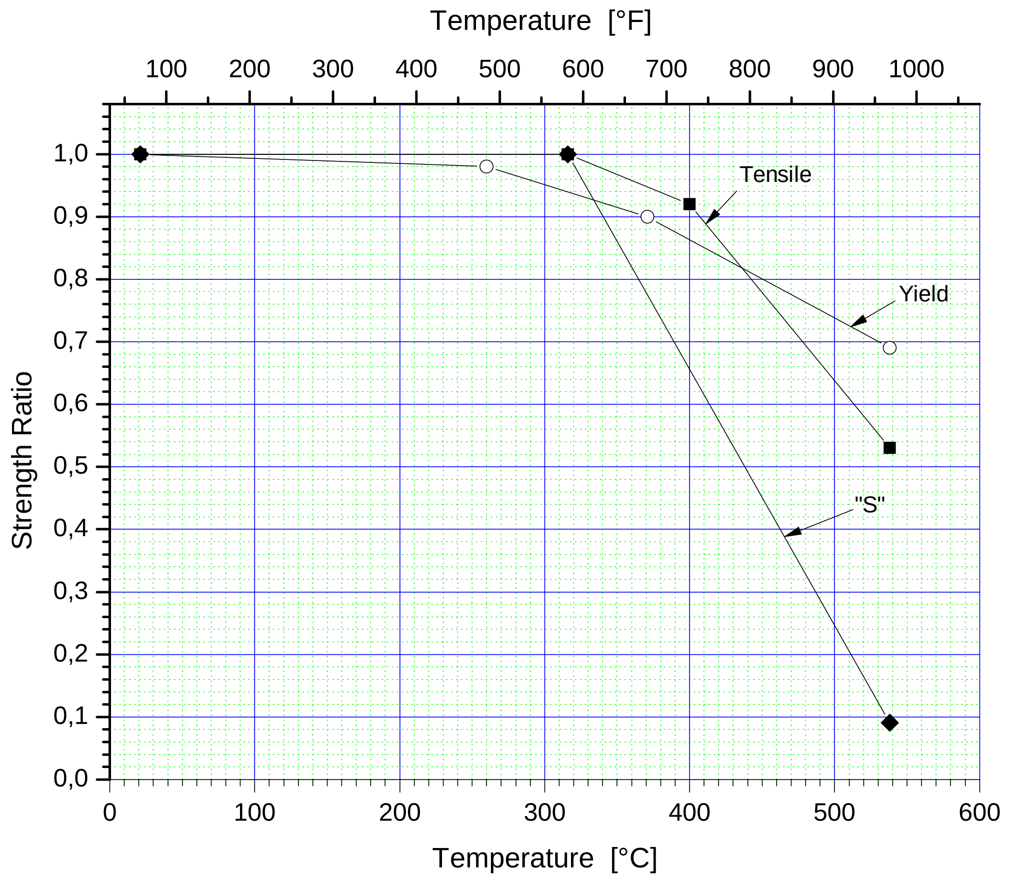


Figure 3.1 Simplified Yield, Tensile and "S" Maximum Allowable Stress Strength Ratio for K55/J55 (Thomas 1967) (B&PVC 2001)

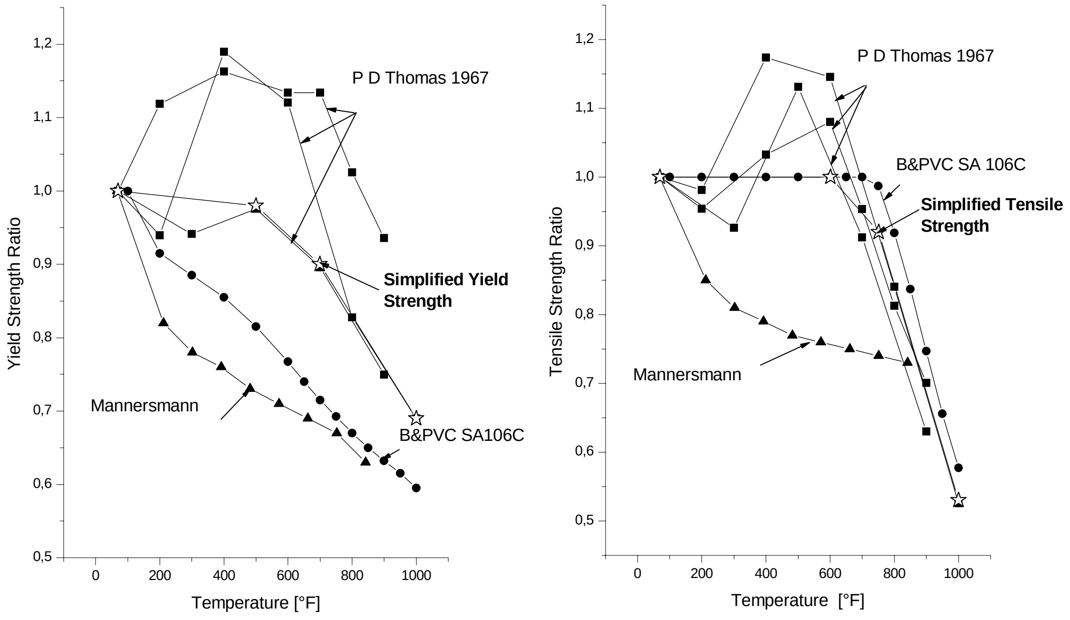


Figure 3.2 Allowable stresses for J-55

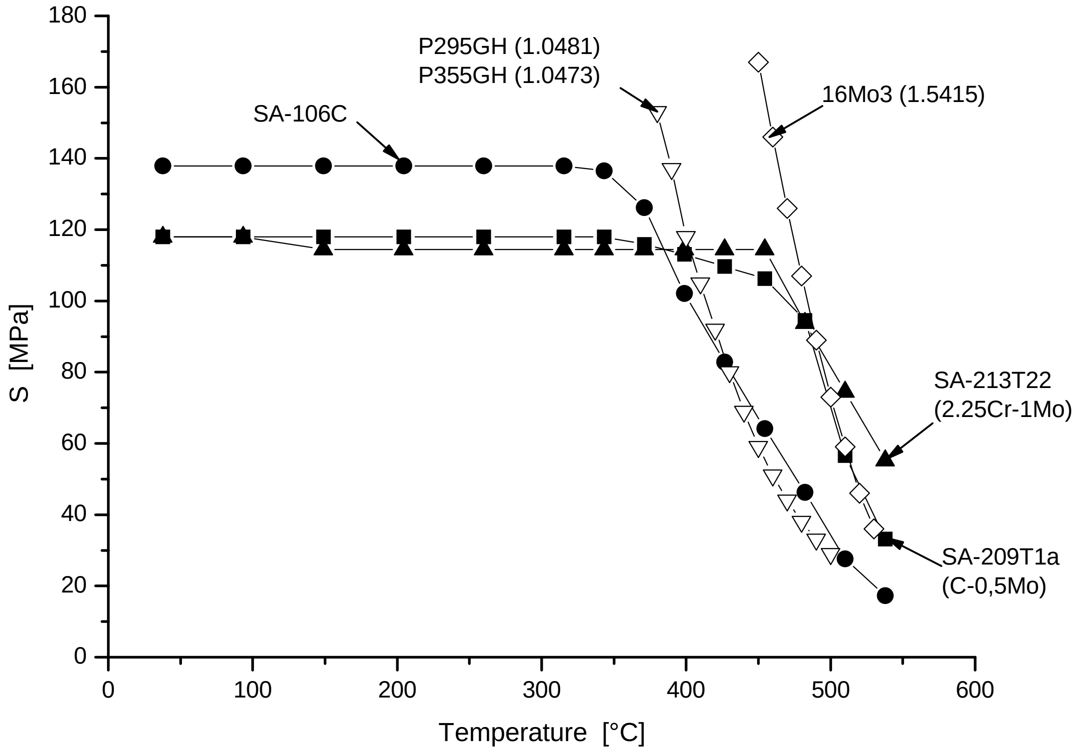


Figure 3.3 Comparison of allowable stresses “S” for selected materials (B&PVC 2001), (ÍST EN 100028-2:1992).

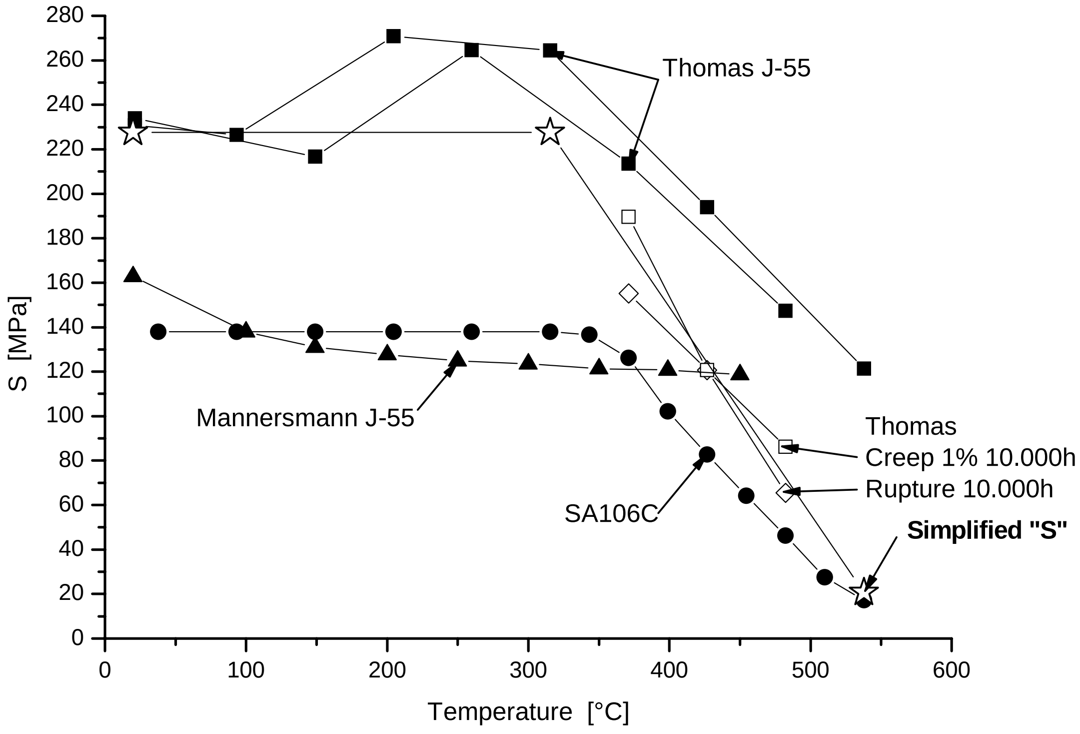


Figure 3.4 Comparison of allowable stresses “S” for J-55 and SA106C (Mannersmann 2002), (Thomas 1967).

4. Corrosion

5. Thermal Strain

5.1 Thermal stresses

In order to define the thermal stresses it is necessary to make two prudent hypotheses (Magneschi et al. 1995):

1) the cement setting temperature of the annulus between the internal and the external casing (or the formation) is between the circulating and the static formation temperature;
2) the casing temperature value after production test depends on the production fluid temperature, which in our case was assumed equal to the bottom hole static formation temperature.

From Figure 5.1 the casing temperature increase, under the hypotheses made, is obtained for each depth. Further Figure 5.2 is a simplified version of Figure 5.1.

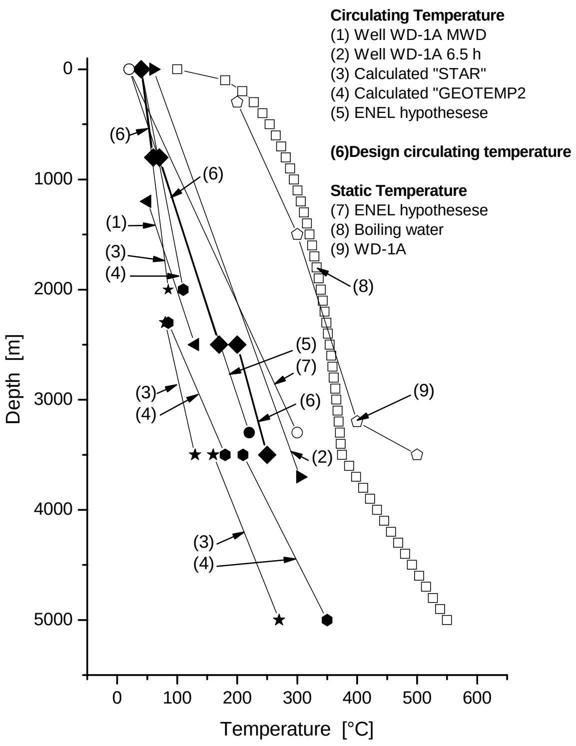


Figure 5.1 Setting temperature for casing (Hefu 2000) (Ikeuchi et al. 1998)

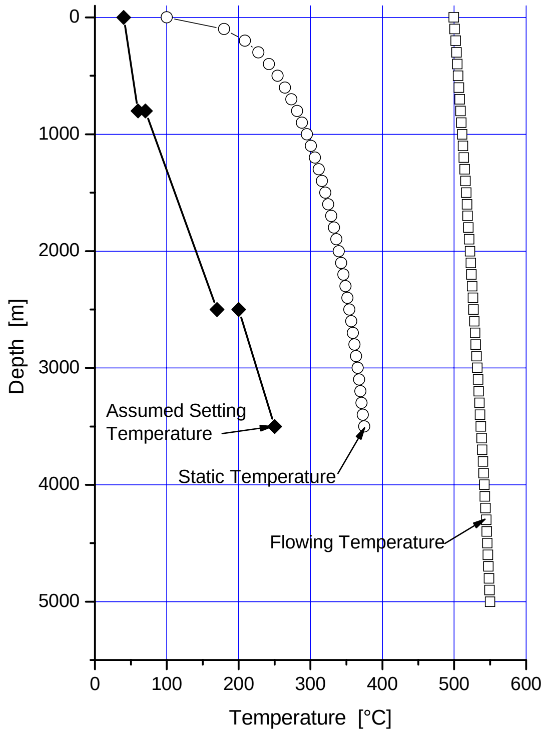


Figure 5.2 Simplified setting temperature for casing

These temperature changes cause strain (tension or compression) due to hindered thermal expansion of the casing, partially offset by possible state of traction that may have been produced during the hardening of the cemented annulus.

The results for different scenarios are shown in Figure 5.3

It is observed that the highest strain is when the casing string is cooled from flowing conditions to 20°C.

5.2 Thermal expansion strain and stress

Stresses which result from restricting the natural growth or contraction of a material due to a temperature change are called thermal stresses (Harvey 1974).

α = coefficient of thermal expansion
μ = Poisson's ratio
E = Modulus of elasticity
T = Temperature

$\sigma = -E\alpha(T_2 - T_1)$ uniaxial thermal stress (one dimensional restraint)
$\sigma = -E\alpha(T_2 - T_1)/(1 - \mu)$ two dimensional restraint
$\sigma = -E\alpha(T_2 - T_1)/(1 - 2\mu)$ three dimensional restraint

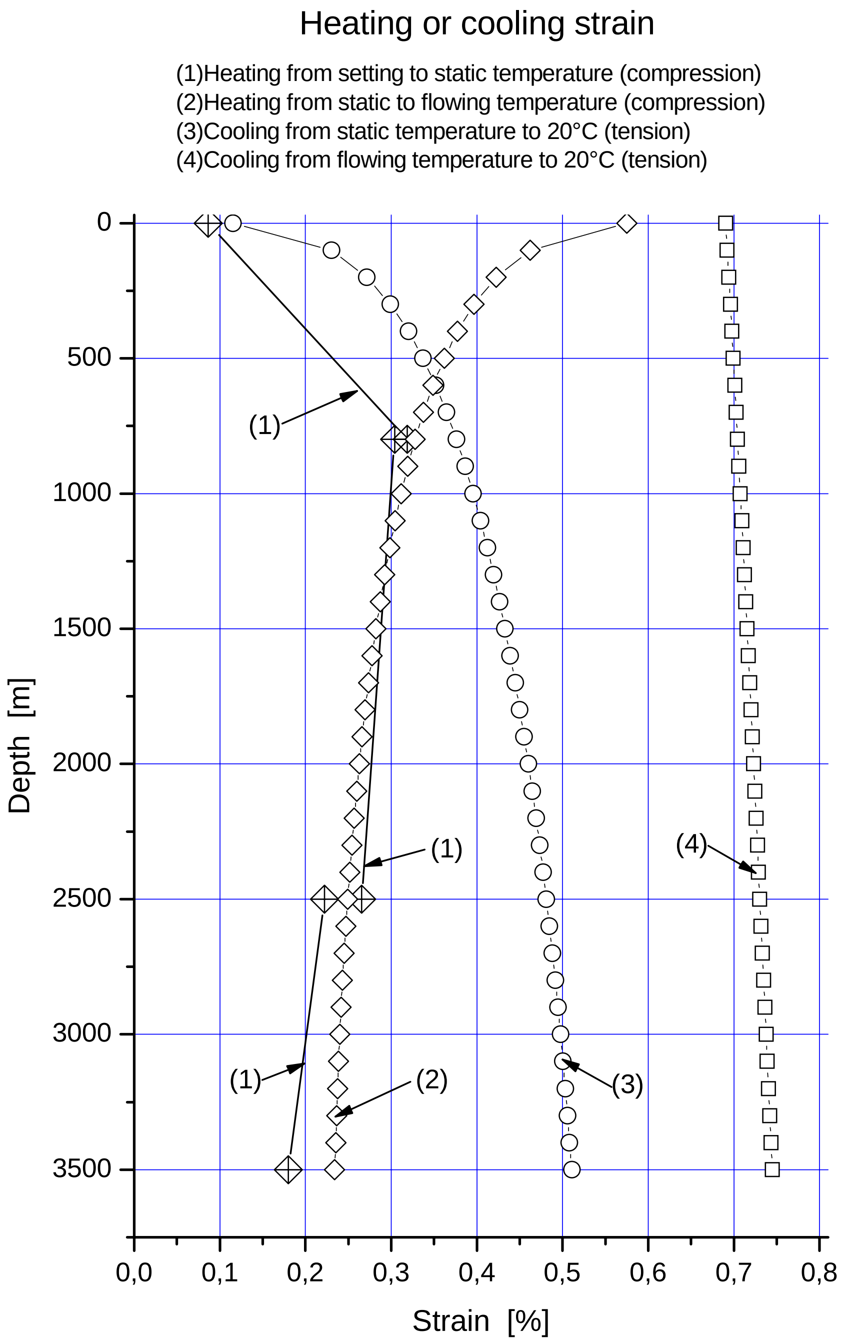


Figure 5.3 One dimensional strain from hindered axial thermal expansion.

5.3 Load during thermal cycling

Thermal cycling is observed in petroleum industry steam injection to enhancement oil well production. Some studies have been carried out among those is “Design Criteria for Completion of Steam injection Wells by Willhite and Dietrich (1967). It is though observed by Maruyama et al. (1990) “that very few experimental data are available on the amount of thermal stress to be expected and the sealing performance of various connections types at steam-injection conditions on which to base casing design.”

Willhite and Dietrich (1967) presented a conceptual model of the thermal load history of the casing during cyclic steam stimulation. “During steam injection, the casing is heated and compressive stress is created in the casing in proportion to the temperature change. If the temperature is high enough, the yield strength of the casing material will be exceeded and the casing will become plastically deformed. Therefore, during the steam-injection phase of stimulation, the casing may fail as result of plastic deformation and the connection may fail as a result of excessive compressive load. When the casing is cooled, the tensile stress generated may be high enough to cause tensile failure of the pipe or the connection. When the casing is cooled to its original temperature (before steam injection), a permanent residual tensile stress will be left in the casing. In addition to creating the potential for tensile failure, this residual tensile stress causes the casing to be more susceptible to biaxial collapse failure."

The study of Maruyama et al. (1990) supports the thermal load history presented by Willhite and Dietrich but shows stress relaxation and early tensile yield. Obviously thermal load phenomena is known in geothermal wells as reported Denc (19970) and Snyder (1979) among others.

The study of Maruyama et al. (1990) "An Experimental Study of Casing Performance under Thermal Cycling Conditions" main objective where

1) "to measure the thermal load history of various casing grades under simulated cyclic steam-stimulation conditions,
2) to test the leak resistance of API connections and the new premium connections at simulated steam-stipulation conditions,
3) to measure the biaxial collapse resistance of the casing materials under tensile loads similar to those generated in the casing during cyclic steam stimulation, and
4) to propose a new casing design approach for thermal wells based on the results of the study experimental measurements."

One thermal cycling in the study consist of heat up period in 3 to 6 hours, maintaining maximum temperature for 24 hours and the cooled by blowing air. Test temperature were 250°C, 300°C and 354°C. Stress relaxation were observed for all tree temperatures even though the holding duration was only 24 hours.

The main conclusion of the study was: "Thick-walled Grade K55 casing with premium connections is a good candidate for high-temperature steam-injection wells."

The conclusion agrees with experience of the geothermal industry and is adopted here except for the top part of the anchor casing where creep is expected.

5.4 Axial Loading

The effects of plastic yield and of stress relaxation with time should be considered when programming casing settings, well operation procedures and down hole workovers. Initial well heating induces compressive stresses in cemented casing. These stresses tend to decrease with time, at rates which may be significant at high temperature and stress levels, and which vary with the microstructure of the particular casing material. Cooling of the well may then develop higher tensile stresses than occurred when the casing string was installed. (Dench 1970)

When pipe fixed at each end is heated, the resulting stress equals that which would be necessary to restore a free, hot pipe to its original length – that is, the modulus′ of elasticity times the thermal expansion. Figure 5.4 is similar to a stress-strain diagram, with strain replaced by temperature. (Dench 1970)

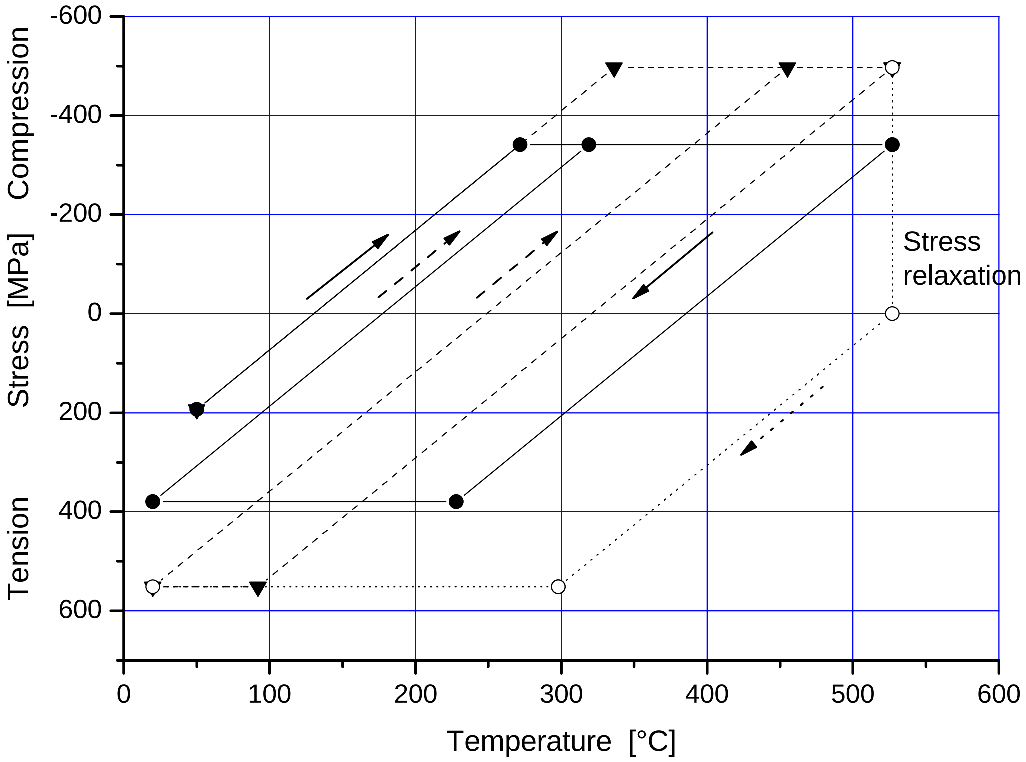


Figure 5.4 Axial thermal loading in casing

6. Creep and Rupture

6.1 Creep and Rupture of Materials at Elevated Temperatures

Many pressure vessels and other engineering structures are subjected simultaneously to action of stress and high temperature. The continual increase in the temperatures of operation has placed great pratical importance on the strength of material at elevated temperatures, and the development of materials to cope with this trend (Harvey 1974).

In general, the strength properties (yield point and ultimate strength) decrease with high temperature while the ductile properties (elongation and reduction in area) increase.

Creep

At elevated temperatures the deformation of metal continue with no increase in stress. This is called "creep" and is defined as the timedependent inelastic deformation of materials.

Creep curves for metals exhibit three characteristic behavior regions. Instantaneous deformation that occures immediately upon application of the load and may contain both elastic and plastic deformation. The primery stage in which the creep is changing at a decreasing rate as a result of strain hardening. The deformation is mainly plastic. The secondary steady stage in which the deformation is plastic . In this stage the creep rate reaches a minimum and remains constant as the effect of strain-hardening is counterbalanced by an annealing influence. Here the creep rate is a function of stress leavel and temerature. The tertiary stage in which the creep continues to increase and is also accompanied by reduction in cross-sectional area and the onset of necking, hence increase in acting stress; thereby, resulting in fracture.

In order to use creep data in design and provide a means of extrapolating creep-stress-time-temperature informations from relatively short periods to that of required life of a structure, a multitude of analytical expressions have evolved. The most commonly used one is the log-log method (see figure 6.1).

One design method frequently used is based on that stress to give a maximum permissible arbitrary amount of creep, usually 0.01 or 0.10 per cent per 1000 hours. corresponding by extrapolation to 1 per cent extension in 10 000 and 100 000 hours. In using creep data, the designer must establish the expected service life and corresponding amount of permissible permanent deformation; and accordingly, choose the stress that satisfies these conditions.

The creep behavior of materials is not only sensitive to stress and time, but also to their environment (atmosphere, neutron irradiation etc.,) physical properties, past strain history, etc.

Creep Rupture

Failure due to creep rupture is an important design consideration. Under constant stress and temperature conditions expexted service life can be established from standard creep rupture data. However, since most members are not subject to either connstant stress or constant temperature , creep-rupture damage criteria which will predict time to rupture in such members having multi-axial states of stress using time to rupture data obtained from tension tests have evolved. Two of these are the "life-fraction" rule and the "strain-fraction" rule.

The strain-fraction rule best fits those materials which exhibit appreciable cracking throughout their life while life-fraction rule is better agreement with those materials which show little cracking until final rupture is approached. Some studies have shown that a geometric mean of these two approaches represents a good over-all data fit. Creep-rupture and fatigue subscribe to the same linear cummulative damage consept. It is reconized that this simple rule cannot fully account for large amounts of strain hardening, metallurical changes and order of loading; accordingly, a damage factor less than unity (0.6 – 1.0) is frequently employed.

Sress Relaxation and Stress Relief

Stress relaxation is relife of stress as a result of creep. It is characterized by the reduction of stress with time while the strain remain constant. Stress relaxation material properties are determined from creep tensile tests where the length of the specimen is maintained constant by decreasing the stress with time. The result is creep stress relaxation curve which relates the remaining or residual stress to time for a constant temperature. The higher the initial stress, the more rapid the relaxation, with the minimum residual stress be coming asymtopic to that stress at which the second stage creep rate is nil. Materials exhibiting low stress relaxation properties are desireable for high temperature bolting. At points of high stress concentation, the rate of creep is large; hence, creep will result in a more favorable stress redistribution. Low residual stresses enhance fatigue life and reduce susceptibility to brittle fracture.

6.2 Temperature sensitivity

The "life-fraction" rule is based on the premise that the expenditure of each individual rupture life-fraction of the total life at elevated temperature is independent of all other fractions of the life to rupture, and that when the fractional life used up at different stress levels and temperature is added up, it will equal unity.

As an example, a cylindrical tube made of 2,25% Cr material with creep-rupture properties shown in Figure 6.1 is initially design for a life of 100 000 hours at 1000°F (538°C) with a stress of 12 000 psi . After 10 000 hours the temperature is increased to 1100°F (593°C) at same stress. The predicted remaining life would then be 0,9 of 3000 hours, or about 113 days. The temperature is changed back to design temperature of 1000°F after 50 days and hence the remaining life in the tube is 46 000 hours Thus the temperature change of 100°F (55°C) for 50 days has lowered the original life expectancy from 100 000 to 56 000 hours or a reduction of 44%. If, instead, the temperature is increased to 1200°F (649°C) the temperature rise of 200°F (111°C) will render remaining life of less than two days.

This quantitative evaluation should emphasize the importance of proper design temperature and material selection for the up most part of the anchor casing.

For the upper limit one should look at the status of material technology for boilers in ultra supercritical pulverized coal power plants. Extensive development in strengthening of 9 to 12% ferritic steels have resulted in temperature/pressure capabilities well over conventional framework of 538°C/17 MPa for the steam. Nearly two dozen plants have been commissioned worldwide with main steam temperatures of 585-600°C and pressures of 25 to 30 MPa (Viswanathan and Bakker 2000).

As previously stated the temperature limit for VIII Division 2 is 700°F (371°C) for carbon steel and low alloy steel and one can look at that temperature as one of the threshold for temperature, which is closely related to the receystallisation temperature at which hardening is increased due to cold forming (for steel at $T_K \geq 400$ °C), deformations which increases with time under constant load creep occurs.

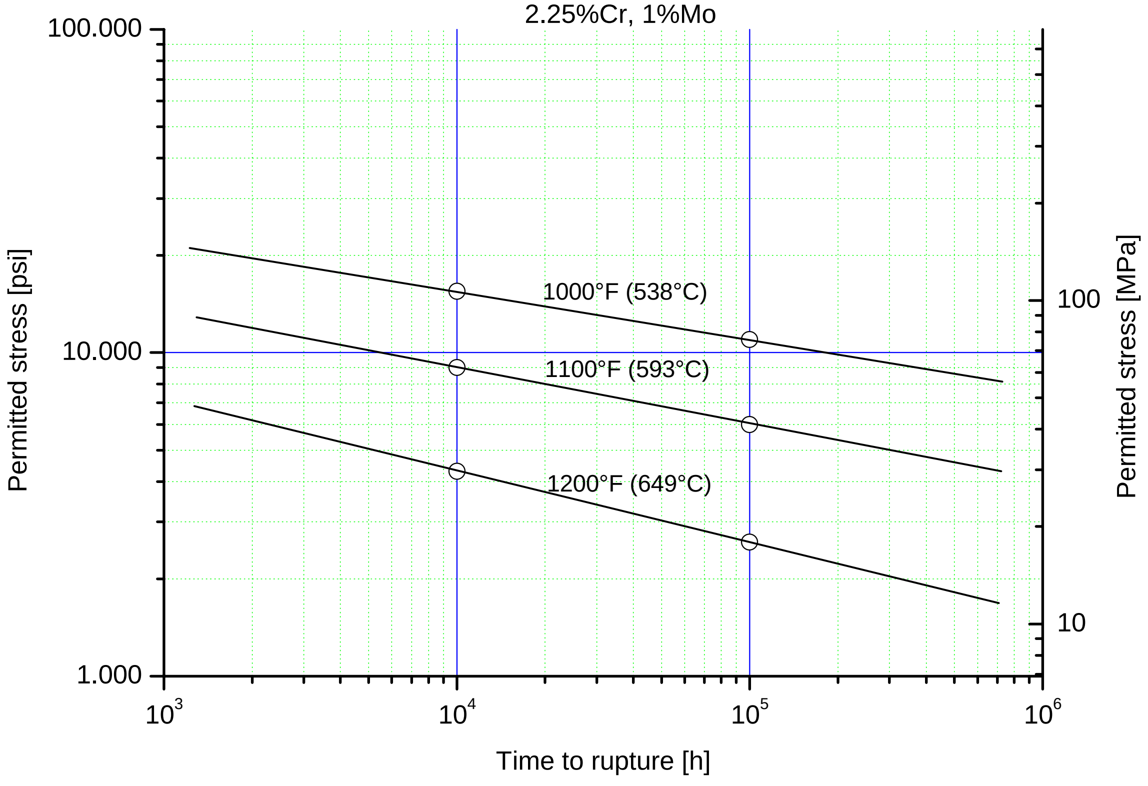


Figure 6.1 Creep rupture curve for 2,25% Chromium 1% Molybdenum steel

7. Cold Well

The following calculations are based on API 5C3, Bulletin on Formulas and Calculations for Casing, Tubing, Drill Pipe, and Line Pipe Properties,

Pipe body yield strength. Pipe body yield strength is the axial load required to yield the pipe. It is taken as the product of the cross-section area and the specified yield strength for the particular grade of pipe.

$$P_y = 0{,}7854\left(D^2 - d^2\right)Y_p$$

Internal yield pressure. The internal yield pressure for threaded and coupled pipe is the lowest of the internal yield pressure for pipe or the internal yield pressure of the coupling.

$$P = 0{,}875\left[\frac{2Y_p t}{D}\right] \quad \text{(factor 0,875 allows for minimum wall)}$$

Collapse pressure. The API subdivides the collapse into four categories

- Yield Strength collapse pressure

$$P_{Y_p} = 2Y_p\left[\frac{(D/t)-1}{(D/t)^2}\right]$$

- Plastic collapse pressure

$$P_P = Y_p\left[\frac{A}{D/t} - B\right] - C$$

- Transient collapse pressure

$$P_T = Y_p\left[\frac{F}{D/t} - G\right]$$

- Elastic collapse pressure

$$P_E = \frac{46{,}95\times10^6}{(D/t)\left((D/t)-1\right)^2}$$

The appropriate formulas to be used for calculating collapse resistance for particular D/t ratio is determined by special formulas, rather than the collapse formula that gives the lowest collapse pressure.

Collapse pressure under axial tension stress. The collapse resistance of casing in the presence of an axial stress is calculated by modifying the yield stress to an axial stress equivalent grade. The modification is based on the Hencky-von Mises maximum strain energy of distortion theory of yielding.

$$Y = \left[\sqrt{1 - 0{,}75\left(S_a / Y_p\right)^2} - 0{,}5S_a / Y_p\right]Y_p$$

Effect of internal pressure on collapse. The external pressure equivalent of external and internal pressure is determined by means of following formula.

$$P_e = P_o - \left(1 - 2/(D/t)\right)P_i$$

The results from various casing diameters for vellprofile A and B are listed in Table 7.1 and 7.2.

Symbols

D = nominal outsude diameter, inc.
d = specified inside diameter, inc
t = nominal wall thickness, inc.
Y_p = minimum yield strength of pipe, psi.
Y_{pa} = yield strength of axial stress equivalent grade, psi.

P_y = pipe body yield strength, psi.
P_Y = minimum yield strength collapse pressure, psi.
P_P = minimum plastic collapse pressure, psi.
P_T = minimum plastic/elastic collapse pressure, psi.
P_E = minimum elastic collapse pressure, psi.
P_e = equivalent external pressure, psi.
P_i = internal pressure, psi.
P_o = external pressure, psi.
S_a = axial stress, psi (tension is positive).

Table 7.1 Internal yield pressure,collapse pressure and cementing pressure in cold well. Wellprofile A

Intermediate casing 18-5/8" – 87,5 lb/ft Grade K55, Casing-shoe at 800 m

	Minimum yield strength	MPa	379,3
	Internal yield pressure	MPa	15,5
	Collapse pressure, zero axial tension stress	MPa	4,3
	Maximum axial tension before cementing	MPa	61,6
	Pressure at well-head		
	Flowing well	MPa	N/A
	Shut-in pressure	MPa	6,4

At casing-shoe (800 m)					
	Collapse pressure, zero axial tension stress		4,3		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	9,6	12,8	15,2
	Internal pressure P_i	MPa	8		
	External pressure equivalent of external and internal pressure	MPa	2,0	5,2	7,6

At 400 m					
	Collapse pressure under axial tension stress	MPa	4,3		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	4,8	6,4	7,6
	Internal pressure P_i	MPa	4		
	External pressure equivalent of external and internal pressure	MPa	1,0	2,6	3,8

Stage cementing at 400 m, pressures at casing-shoe					
	Collapse pressure, zero axial tension stress	MPa	4,3		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	4,8	6,4	7,6
	Internal pressure P_i	MPa	4		
	External pressure equivalent of external and internal pressure	MPa	1,0	2,6	3,8

Table 7.1 cont. Internal yield pressure,collapse pressure and cementing pressure in cold well. Wellprofile A

Anchor casing 13-3/8" – 68 lb/ft Grade K55, Casing-shoe at 2400 m

	Minimum yield strength	MPa	379,3
	Internal yield pressure	MPa	23,8
	Collapse pressure, zero axial tension stress	MPa	13,4
	Maximum axial tension before cementing	MPa	184,8
	Pressure at well-head		
	Flowing well	MPa	19,5
	Shut-in pressure	MPa	22,1

At casing-shoe (2400 m)					
	Collapse pressure, zero axial tension stress	MPa	13,4		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	28,8	38,4	45,6
	Internal pressure P_i	MPa	24		
	External pressure equivalent of external and internal pressure	MPa	6,5	16,1	23,3

At 1200 m					
	Collapse pressure under axial tension stress	MPa	12,4		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	14,4	19,2	22,8
	Internal pressure P_i	MPa	12		
	External pressure equivalent of external and internal pressure	MPa	3,3	8,1	11,7

Stage cementing at 800 m, pressures at casing-shoe					
	Collapse pressure, zero axial tension stress	MPa	12,4		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	9,6	12,8	15,2
	Internal pressure P_i	MPa	8		
	External pressure equivalent of external and internal pressure	MPa	2,2	5,4	7,8

Table 7.1 cont. Internal yield pressure,collapse pressure and cementing pressure in cold well. Wellprofile A

Production casing 9-5/8" – 47 lb/ft Grade K55, Casing-shoe at 3500 m

	Minimum yield strength	MPa	379,3
	Internal yield pressure	MPa	32,6
	Collapse pressure, zero axial tension stress	MPa	26,8
	Maximum axial tension before cementing	MPa	269,5
	Pressure at well-head		
	Flowing well	MPa	19,5
	Shut-in pressure	MPa	25

At casing-shoe (3500 m)					
	Collapse pressure, zero axial tension stress	MPa	26,8		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	42,0	56,0	66,5
	Internal pressure P_i	MPa	35		
	External pressure equivalent of external and internal pressure	MPa	10,4	24,4	34,9

At 1750 m					
	Collapse pressure under axial tension stress	MPa	22,8		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	21,0	28,0	33,3
	Internal pressure P_i	MPa	17,5		
	External pressure equivalent of external and internal pressure	MPa	5,2	12,2	17,5

Stage cementing at 2400 m, pressures at casing-shoe					
	Collapse pressure, zero axial tension stress	MPa	26,8		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	28,8	38,4	45,6
	Internal pressure P_i	MPa	24		
	External pressure equivalent of external and internal pressure	MPa	7,2	16,8	24,0

Maruyama et al 1990 observed that for as-rolled material, a work-hardening material such as Grade K55 casing, the biaxial collapse resistance is much higher than predicted by API equation and conclude that it seems reasonable to take advantage of the work-hardening characteristic of as-rolled material in design thermal-well casing.

Table 7.2 Internal yield pressure,collapse pressure and cementing pressure in cold well.
Wellprofile B

Intermediate casing 13-3/8" – 68 lb/ft Grade K55, Casing-shoe at 800 m

	Minimum yield strength	MPa	379,3
	Internal yield pressure	MPa	23,8
	Collapse pressure, zero axial tension stress	MPa	13,4
	Maximum axial tension before cementing	MPa	61,6
	Pressure at well-head		
	Flowing well	MPa	N/A
	Shut-in pressure	MPa	6,4

At casing-shoe (800 m)					
	Collapse pressure, zero axial tension stress	MPa	13,4		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	9,6	12,8	15,2
	Internal pressure P_i	MPa	8		
	External pressure equivalent of external and internal pressure	MPa	2,2	5,4	7,8

At 400 m					
	Collapse pressure under axial tension stress	MPa	13,2		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	4,8	6,4	7,6
	Internal pressure P_i	MPa	4		
	External pressure equivalent of external and internal pressure	MPa	1,1	2,7	3,9

Stage cementing at 400 m, pressures at casing-shoe					
	Collapse pressure, zero axial tension stress	MPa	13,4		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	4,8	6,4	7,6
	Internal pressure P_i	MPa	4		
	External pressure equivalent of external and internal pressure	MPa	1,1	2,7	3,9

Table 7.2 cont. Internal yield pressure,collapse pressure and cementing pressure in cold well. Wellprofile B

Anchor casing 10-3/4" – 51 lb/ft Grade K55, Casing-shoe at 2400 m

	Minimum yield strength	MPa	379,3
	Internal yield pressure	MPa	27,8
	Collapse pressure, zero axial tension stress	MPa	18,7
	Maximum axial tension before cementing	MPa	184,8
	Pressure at well-head		
	Flowing well	MPa	18,5
	Shut-in pressure	MPa	22,1

At casing-shoe (2400 m)					
	Collapse pressure, zero axial tension stress	MPa	18,7		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	28,8	38,4	45,6
	Internal pressure P_i	MPa	24		
	External pressure equivalent of external and internal pressure	MPa	6,8	16,4	23,6

At 1200 m					
	Collapse pressure under axial tension stress	MPa	17,4		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	14,4	19,2	22,8
	Internal pressure P_i	MPa	12		
	External pressure equivalent of external and internal pressure	MPa	3,4	8,2	11,8

Stage cementing at 800 m, pressures at casing-shoe					
	Collapse pressure, zero axial tension stress	MPa	18,7		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	9,6	12,8	15,2
	Internal pressure P_i	MPa	8		
	External pressure equivalent of external and internal pressure	MPa	2,3	5,5	7,9

Table 7.2 cont. Internal yield pressure,collapse pressure and cementing pressure in cold well. Wellprofile B

	Production casing 7-5/8” – 33,7 lb/ft Grade K55, Casing-shoe at 3500 m

	Minimum yield strength	MPa	379,3
	Internal yield pressure	MPa	37,4
	Collapse pressure, zero axial tension stress	MPa	35,2
	Maximum axial tension before cementing	MPa	269,5
	Pressure at well-head		
	Flowing well	MPa	18,0
	Shut-in pressure	MPa	25

At casing-shoe (3500 m)					
	Collapse pressure, zero axial tension stress	MPa	35,2		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	42,0	56,0	66,5
	Internal pressure P_i	MPa	35		
	External pressure equivalent of external and internal pressure	MPa	10,9	24,9	35,4

At 1750 m					
	Collapse pressure under axial tension stress	MPa	29,2		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	21,0	28,0	33,3
	Internal pressure P_i	MPa	17,5		
	External pressure equivalent of external and internal pressure	MPa	5,5	12,5	17,7

Stage cementing at 2400 m, pressures at casing-shoe					
	Collapse pressure, zero axial tension stress	MPa	35,2		
	Cement specific gravity		1,2	1,6	1,9
	External pressure after cementing P_o	MPa	28,8	38,4	45,6
	Internal pressure P_i	MPa	24		
	External pressure equivalent of external and internal pressure	MPa	7,5	17,1	24,3

Table 73 Results of Collapse resistance calculations

		Casing shoe				
		m				
Cement specific gravity				1,2	1,6	1,9
Well profile A						
	18-5/8”	800		Not required	Required	Required
	13-3/8”	2400		Not required	Required	Required
	9-5/8”	3500		Not required	Not required	Required
Well profile B						
	13-3/8”	800		Not required	Not required	Not required
	10-3/4”	2400		Not required	Not required	Required
	7-5/8”	3500		Not required	Not required	Required

The temperature dependent of collapse resistance for zero axial stress is shown in Figure 7.1 for selected casing sizes.

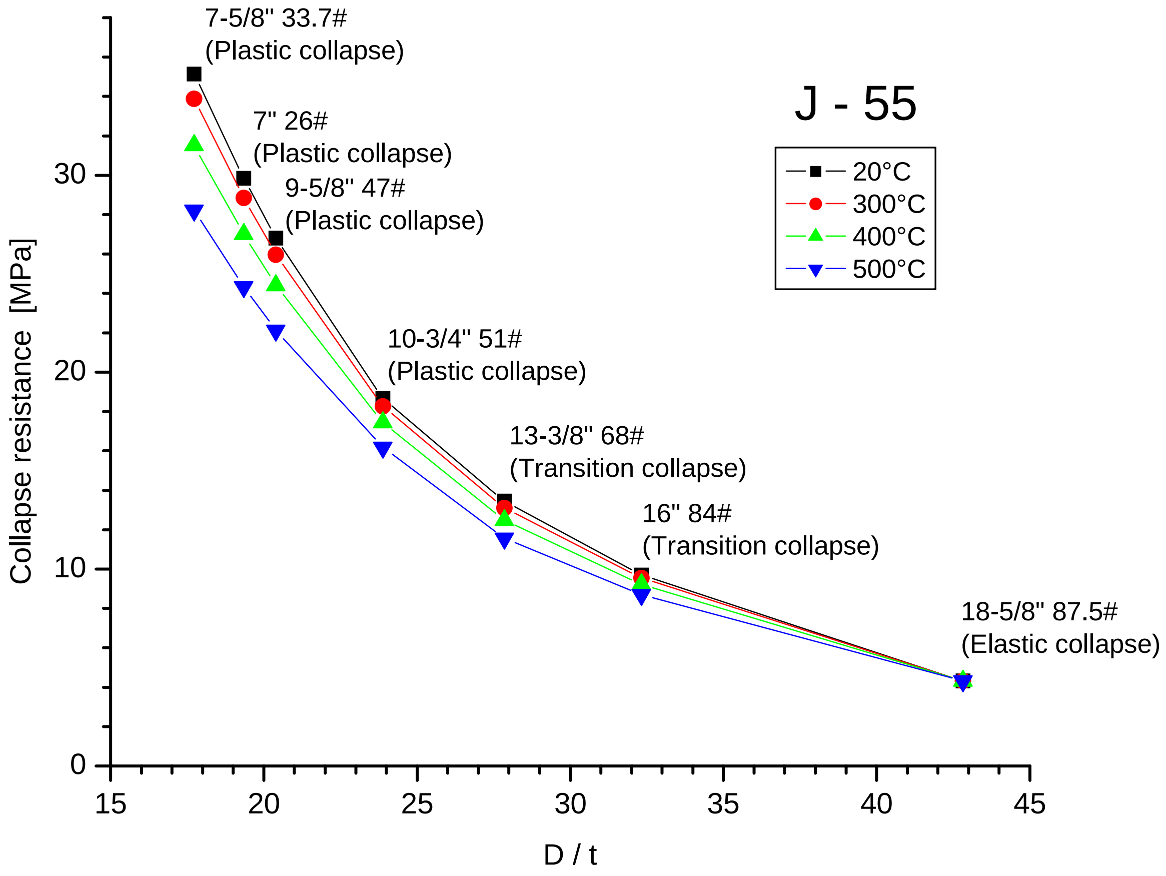


Figure 7.1 Collapse resistance as a function of diameter/wall thickness ratio and temperature

Biaxial collapse resitance

Collapse pressure with axial tensile load.

Quenched-and-tempered casing and as-rolled casing showed significantly different collapse-resistance characteristics under tensile loads.

Maruyama et al. (1990)concludes that the biaxial collapse pressure depends on the stress-strain characteristics of the materials. For the quenched-and- tempered material, a perfect elastic/plastic material, the biaxial collapse pressure is predicted adequately by the API equation. Because Grades L80, C95, and P110 casing are all quenched-and tempered materials, it was expected that their biaxial collapse resistance can be predicted by the API equation. For the as-rolled material, a work-hardening material, the biaxial collapse collapse is much higher than that predicted by the API equation. It seems reasonable to take advantage of this work-hardening characteristic of the as-rolled material in designing thermal-well casing.

The expansion of trapped liquid.

The maximum pressure possible from the thermal expansion of a trapped fluid far exceeds the strength of normal casing strings in either burst or collapse. Because it is important to retain the integrity of the production string, any failure should to occur in the outer string. Thus, for the final pair of adjacent cemented casing, the collapse resistance of the inner string shall exceed the burst strength of the outer string. The design factor ratio of production casing collapse resistance /outer casing internal yield pressure shall be not less than 1,2 (NZS 2403:1991)

Table 7.4 Collapse/burst ratio

			20 °C	300°C	400°C	500°C
Well profile A						
	Anchor casing 13-3/8”					
	Internal Yield Pressure	MPa	13,8	22,6	20,5	17,6
	Production casing 9-5/8”					
	Collapse resistance	MPa	26,8	26	24,4	22,1
	Collapse/burst Ratio		1,13	1,15	1,19	1,26
Well profile B						
	Anchor casing 10-3/4”					
	Internal Yield Pressure	MPa	27,8	26,4	23,9	20,6
	Production casing 7-5/8”					
	Collapse resistance	MPa	35,1	33,9	31,5	28,2
	Collapse/burst Ratio		1,26	1,28	1,32	1,37

From Table 7.3 can be gleaned that the requirements are met for well profile B but not for well profile A. There the ratio is 1,13 at 20°C but improves with higher temperature to 1,19 at 400°C and 1.26 at 500°C.

8. Hot Well

8.1 Normal Stresses (Harvey 1974).

General expressions for normal stresses are:

$$\sigma_r = \frac{a^2 p_i - b^2 p_o}{b^2 - a^2} - \frac{(p_i - p_o)a^2 b^2}{r^2(b^2 - a^2)}$$ radial stress, and

$$\sigma_t = \frac{a^2 p_i - b^2 p_o}{b^2 - a^2} + \frac{(p_i - p_o)a^2 b^2}{r^2(b^2 - a^2)}$$ hoop stress (tangential stress)

Inspection of above equations indicate that the maximum value of σ_t occurs at the inner surface, and maximum σ_r will always be the larger of the two pressures, p_i and p_o.

These equations are known as Lamer solution, or thick-cylinder formulars. It is noted that the sum of these two stresses remains constant; hence the deformation of all elements in the axial direction is the same, and cross sections of the cylinder remain plane after deformation.

σ_r = radial stress
σ_t = hoop stress (tangential stress)
p_i = internal pressure
p_o = external pressure
a = inner radius
b = outer ratius
r = radius

In our case the expression for axial stress is:

$\sigma_z = -E\,\alpha\,\Delta T$ axila (longitudinal) stress

σ_z = axila (longitudinal) stress
E = modulus of elasticity
α = coefficient of thermal expansion
ΔT = temperature difference

The results from normal stress calculations are listed in Table 8.1 for wellprofile A and in Table 8.2 for wellprofile B.

TABLE 8.1 Normal Stresses, Wellprofile A

Casing	18-5/8” 87,5 #			13-3/8” 68#			9-5/8” 47#	
	inner surface	outer surface		inner surface	outer surface		inner surface	outer surface
Well flowing								
at surface	wellhead			wellhead			wellhead	
p_i MPa	16,8	16,8		25	25		25	25
p_o MPa	0	0		0	0		0	0
ΔT °C	176-300	176-300		250-400	250-400		250-400	250-400
σ_r MPa	-16,8	0		-25	0		-25	0
σ_t MPa	351,4	334,6		336,3	311,3		243,0	218,0
σ_z MPa	-440-752	-440-752		-626-1002	-626-1002		-626-1002	-626-1002
Well flowing								
at casing shoe	800			2500			3500	
p_i MPa	16,8	16,8		25	25		25	25
p_o MPa	6,5	6,5		16,8	16,8		22,1	22,1
ΔT °C	176-300	176-300		263-426	263-426		270-440	270-440
σ_r MPa	-16,8	-6,5		-25	-16,8		-25	-22,1
σ_t MPa	209,0	198,7		93,5	85,3		6,1	3,2
σ_z MPa	-440-752	-440-752		-659-1067	-659-1067		-679-1102	-676-1102
Boiling point conditions								
at casing shoe	800			2500			3500	
p_i MPa	16,8	16,8		25	25		25	25
p_o MPa	6,5	6,5		16,8	16,8		22,1	22,1
ΔT °C	141-230	141-230		176-252	176-252		188-275	188-275
σ_r MPa	-16,8	-6,5		-25	-16,8		-25	-22,1
σ_t MPa	209,0	198,7		93,5	85,3		6,1	3,2
σ_z MPa	-352-576	-352-576		-441-631	-441-631		-470-689	-470-689

TABLE 8.2 Normal Stresses, Wellprofile B

Casing	13-3/8” 68 #			10-3/4” 51#			7-5/8” 33,7#	
	inner surface	outer surface		inner surface	outer surface		inner surface	outer surface
Well flowing								
at surface	wellhead			wellhead			wellhead	
p_i MPa	16,8	16,8		25	25		25	25
p_o MPa	0	0		0	0		0	0
ΔT °C	176-300	176-300		250-400	250-400		250-400	250-400
σ_r MPa	-16,8	0		-25	0		-25	0
σ_t MPa	226,0	209,2		286,6	261,6		209,9	184,9
σ_z MPa	-440-752	-440-752		-626-1002	-626-1002		-626-1002	-626-1002
Well flowing								
at casing shoe	800			2500			3500	
p_i MPa	16,8	16,8		25	25		25	25
p_o MPa	6,5	6,5		16,8	16,8		22,1	22,1
ΔT °C	176-300	176-300		263-426	263-426		270-440	270-440
σ_r MPa	-16,8	-6,5		-25	-16,8		-25	-22,1
σ_t MPa	132,1	121,8		77,2	69,0		2,3	-0,6
σ_z MPa	-440-752	-440-752		-659-1067	-659-1067		-679-1102	-676-1102
Boiling point conditions								
at casing shoe	800			2500			3500	
p_i MPa	16,8	16,8		25	25		25	25
p_o MPa	6,5	6,5		16,8	16,8		22,1	22,1
ΔT °C	141-230	141-230		176-252	176-252		188-275	188-275
σ_r MPa	-16,8	-6,5		-25	-16,8		-25	-22,1
σ_t MPa	132,1	121,8		77,2	69,0		2,3	-0,6
σ_z MPa	-352-576	-352-576		-441-631	-441-631		-470-689	-470-689

8.2 Buckling

Buckling, thermal stresses

Cement placement, lost circulation, hole washout, and dissolution (leaching) of even well placed and cured cement may leave an interval of casing without lateral support. Temperature increase causes pipe elongation and if the unsupported interval is long enough, the pipe will buckle. Neglecting pressure effects, Euler's formula for columnar buckling, with both ends constrained is (Snyder 1979):

$$S_c = 4\,\pi^2\,E/(L/r_g)^2$$

Where

S_c = Critical stress for the column, psi
E = Modulus of elasticity for steel, psi
L = Length of unsupported column, inches
r_g = Radius of gyration, inches

In this expression, $r_g = (d_o^2 + d_i^2)^{1/2}/4$. Note that critical stress 1) increases with casing diameter 2) decreases with length and 3) decreases with wall thickness. The significant effect of diameter is illustrated in figure 8.1.

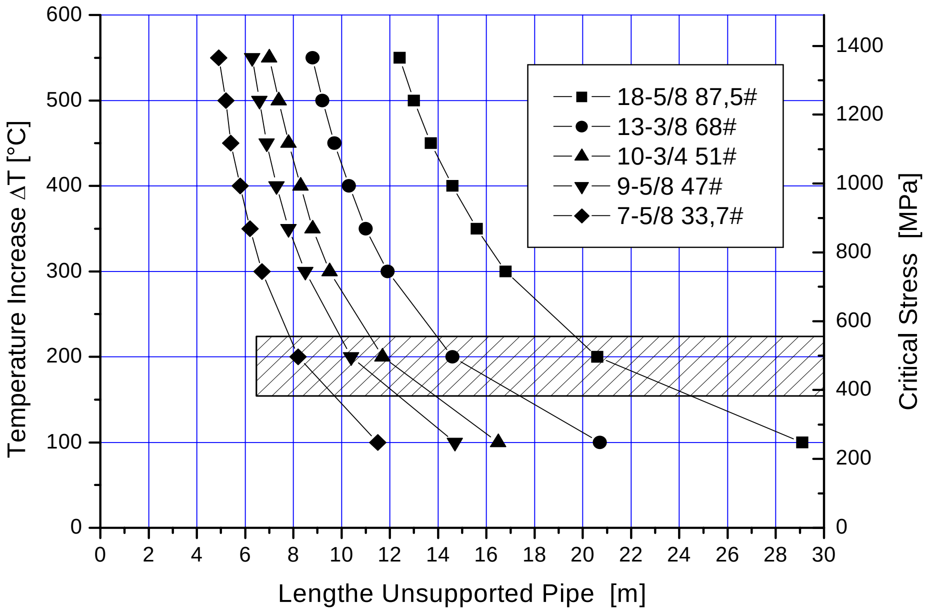


Figure 8.1 Buckling tendencies of five sizes of casing

Casing can also failed from tensile stresses when it is cemented solidly. The expression for stress, that is independent of length, is:

$\sigma = -\,E\alpha(T_2 - T_1)$ uniaxial thermal stress (one dimensional restraint)

α = coefficient of thermal expansion
E = Modulus of elasticity
T = Temperature

The minimum buckling force for a very long pipe is a function of pipe properties and the elastic modulus of the surrounding medium. For field condition, the modulus of surrounding cement or soil needed to avoid buckling is generally small.

A laboratory experiment was devised and used to evaluate the effect of various supporting cements outside a thin walled tube. The tube was subjected to compressive casing strains well beyond its elastic limit while appropriate stress conditions were maintained inside the tube and in the cement and soil around it. Through the elastic loading region and into the plastic region (maximum axial pipe strain of 0,70%), the pipe did not buckle when supported by the cement even though irreversible shortening was experienced (Wilson et al. 1979).
Experiments have demonstrated that surrounding cements can readily prevent axial buckling even though the pipe body is strained axially well beyond the yield point.

8.3 Creep Design

The 2001 B&PVC Section VIII – Division 1, Subsection A General Requirements, part DESIGN PART UG is applied for this calculation.
General. The design of pressure vessels and vessels parts shall conform to the general design requirements in the following paragraphs.
Design Temperature. The maximum temperature used in design shall be not less than the mean metal temperature (through the thickness) expected under operating conditions for the part considered.
Design Pressure. Vessels shall be design for at least the most severe condition of coincident pressure and temperature expected in normal operation. For this condition and test conditions, the maximum difference in pressure between the inside and outside of the vessel.
Loadings. The loadings to be considered in designing a vessel shall include those from: internal or external design pressure; weight of the vessel and normal contents under operating or test conditions; superimposed static reactions from weight of attached equipment;
Maximum Allowable Stress Values. The maximum allowable stress is the maximum unit stress permitted in a given material used in a vessel constructed under these rules. The maximum allowable tensile stress values permitted for different materials are given in Subpart 1 of Section II, Part D.
The wall thickness of a vessel computed by these rules shall be determined such that, for any combination of loading that induce primary stress and are expected to occur simultaneously during normal operation of the vessel, the induced maximum general primary membrane stress does not exceed the maximum allowable stress value in tension.
The maximum allowable stress values that are to be used in thickness calculations are to be taken from the tables at the temperature which is expected to be maintained in the metal under conditions of loading being considered. Maximum stress values may be interpolated for intermediate temperatures.
Corrosion. Corrosion allowances shall be specified.

Thickness of Shells Under Internal Pressure

The thickness of shells under internal pressure shall be not less than that computed by the following formulas. In addition, provision shall be made for any of the other loadings when such loading are expected.
The symbols defined below are used in the formulas of this paragraph.

t= minimum required thickness of shell, in. (mm)
P= internal design pressure psi (kPa)
R= inside radius of the shell course under consideration, in. (mm) (For pipe, the inside radius R is determined by the nominal outside radius minus the normal wall thickness.)
S= maximum allowable stress value, psi (kPa)
E= joint efficiency for, or efficiency of, appropriate joint in cylindrical shells

Cylindrical Shells. The minimum thickness or maximum allowable working pressure of cylindrical shells shall be the greater thickness or lesser pressure as given by (1) or (2) below.

(1) *Circumferential Stress (Longitudinal Joints).*
When the thickness does not exceed one-half of the inside radius, or P does not exceed 0.385 SE, the following formulas shall apply:

$t = PR/(SE - 0,6\,P)$ or $P = SEt/(R + 0.6t)$

(2) Longitudinal Stress (Circumferential Joints
When the thickness does not exceed one-half of the inside radius, or P does not exceed 1.25SE, the following formulas shall apply:

$t = PR/(2SE + 0.4P)$ or $P = 2SEt/(R - 0.4t)$

The results are listed in Table 8.3 for 13-3/8" anchor casing for wellprofile A and in table 8.4 for 10-3/4" anchor casing for wellprofile B-1

According to the New Zealand code of practice for Deep Geothermal Wells the top section of the anchor casing, to 25m below ground level, shall also be designed to comply with the ASME Boiler and Pressure Vessel Code in respect of steel pipe grade and thickness, in any situation where the ASME requirements exceed those calculated for casing (NZS 2403:1991).

Table 8.3 Wellprofile A, anchor casing 13,375”

Well-head		Flowing condition				Column of saturated steam				Empty well			
		19,5 MPa 500°C				**19,7 MPa 364°C**				**25 MPa 20°C**			
Internal design pressure	P MPa	19,5	19,5	19,5	19,5	19,7	19,7	19,7	19,7	25	25	25	25
Internal radius	R mm	157,65	157,65	157,65	157,65	157,65	157,65	157,65	157,65	157,65	157,65	157,65	157,65
Design temperature	°C	500	500	500	500	370	370	370	370	20	20	20	20
	°F	932	932	932	932	698	698	698	698	68	68	68	68
Material		SA106C	C-0,5Mo	2,5Cr-1Mo	J-55	SA106C	C-0,5Mo	2,5Cr-1Mo	J-55	SA106C	C-0,5Mo	2,5Cr-1Mo	J-55
Maximum allowable stress values (Table 3.6)	S kpi	5	10,2	11,8	7,92	18,3	16,8	16,6	25,5	20	17,1	17,1	33
	S MPa	34,5	70,3	81,4	54,6	126,2	115,9	114,5	175,9	137,9	117,9	117,9	227,6
Circumfeential Stress (Longitudial Joints) (UG-27, (c), (1))													
Joint efficiency	E	1	1	1	1	1	1	1	1	1	1	1	1
Thickness of shell	**t mm**	**134,9**	**52,4**	**44,1**	**71,6**	**27,2**	**29,9**	**30,3**	**18,9**	**32,1**	**38,3**	**38,3**	**18,5**
t<R/2	R/2	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8
P<0,385 S E	0,385 SE	13,3	27,1	31,3	21,0	48,6	44,6	44,1	67,7	53,1	45,4	45,4	87,6
Longitudial Stress (Circumferential Joint) (UG-27, (c), (2))													
Joint efficiency	E	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8
Thickness of shell	**t mm**	48,8	25,5	22,3	32,3	14,8	16,1	16,3	10,7	17,1	19,8	19,8	10,5
t<R/2	R/2	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8	78,8
P<1,25 S E	1,25 SE	34,5	70,3	81,4	54,6	126,2	115,9	114,5	175,9	137,9	117,9	117,9	227,6
Outside Diameter	D mm	585	420	403,5	458,5	374	379	380,3	355,9	379	392	391,9	352,4
	D inc	23,0	16,5	15,9	18,1	14,7	14,9	15,0	14,0	14,94	15,43	15,4	13,9

Table 8.4 Well profile B, anchor casing 10,750”

Well-head		Flowing condition				Column of saturated steam				Empty well			
		18,0 MPa 475°C				**19,7 MPa 364°C**				**25 MPa 20°C**			
Internal design pressure	P MPa	18,0	19,7	19,7	19,7	19,7	19,7	19,7	19,7	25	25	25	25
Internal radius	R mm	125,1	125,1	125,1	125,1	125,1	125,1	125,1	125,1	125,1	125,1	125,1	125,1
Design temperature	°C	475	475	475	475	370	370	370	370	20	20	20	20
	°F	887	887	887	887	698	698	698	698	68	68	68	68
Material		SA106C	C-0,5Mo	2,5Cr-1Mo	J-55	SA106C	C-0,5Mo	2,5Cr-1Mo	J-55	SA106C	C-0,5Mo	2,5Cr-1Mo	J-55
Maximum allowable stress values (Table 3.6)	S kpi	7	14	14	11	18,3	16,8	16,6	25,5	20	17,1	17,1	33
	S MPa	48,3	96,6	96,6	75,9	126,2	115,9	114,5	175,9	137,9	117,9	117,9	227,6
Circumfeential Stress (Longitudial Joints) (UG-27, (c), (1))													
Joint efficiency	E	1	1	1	1	1	1	1	1	1	1	1	1
Thickness of shell	**t mm**	**60,1**	**26,3**	**26,3**	**34,6**	**21,5**	**23,7**	**24,0**	**15,0**	**25,4**	**30,4**	**30,4**	**14,7**
t<R/2R/2		62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6
P<0,385 S E0,385 SE		18,6	37,2	37,2	29,2	48,6	44,6	44,1	67,7	53,1	45,4	45,4	87,6
Longitudial Stress (Circumferential Joint) (UG-27, (c), (2))													
Joint efficiency	E	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8
Thickness of shell	**t mm**	26,7	13,9	13,9	17,5	11,7	12,8	12,9	8,5	13,6	15,7	15,7	8,4
t<R/2R/2		62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6	62,6
P<1,25 S E1,25 SE		48,3	96,6	96,6	75,9	126,2	115,9	114,5	175,9	137,9	117,9	117,9	227,6
Outside Diameter	D mm	370	303	302,7	319,4	374	379	380,3	355,9	379	392	391,9	352,4
	D inc	14,4	11,9	11,9	12,6	11,7	11,9	11,9	11,1	11,85	12,24	12,2	11,0

The result of the casing design is summarised in the following:

- For the materials consider for the top part of the anchor casing 2,5Cr-1Mo (SA-213 T22) is consider the best suited material for the time being. The wall thickness of the 13-3/8" anchor casing is 44 mm and for 10-3/4" 31 mm.

- Thick walled grade K-55 casing with premium connections is the best suited for high temperature operation and is planed for the other part of the casing program. Premium connections with metal to metal seals and of higher grade material of quenched and temper steel containing molybdenum is considered to render adequate seal and strength.

- Successful cementing of casings is the basis for safe operation of the well and thermal cycling should be kept to minimum to enhance the lifetime of the well.

The corresponding casing program is presented in the following table:

Table 8.5 Casing wall thickness and material

	Casing outside diameter	Normal weight of casing	Wall thickness	Casing Depth	Material
	Inc	lbs/ft	mm	m	
Wellprofile A					
Surface casing	22-1/2			400	K55
Intermediate casing	18-5/8	87,5	11,05	800	K55
Anchor casing	13-3/8	68,0	44,1 / 12,19	2400	2,5Cr-1Mo / K55
Production casing	9-5/8	47,0	11,99	3500	K55
Wellprofile B					
Surface casing	18-5/8	87,5	11,05	400	K55
Intermediate casing	16	84,0	12,57	800	K55
Anchor casing	10-3/4	51,0	30,4 / 11,43	2400	2,5Cr-1Mo / K55
Production casing	7-5/8	33,7	10,92	3500	K55

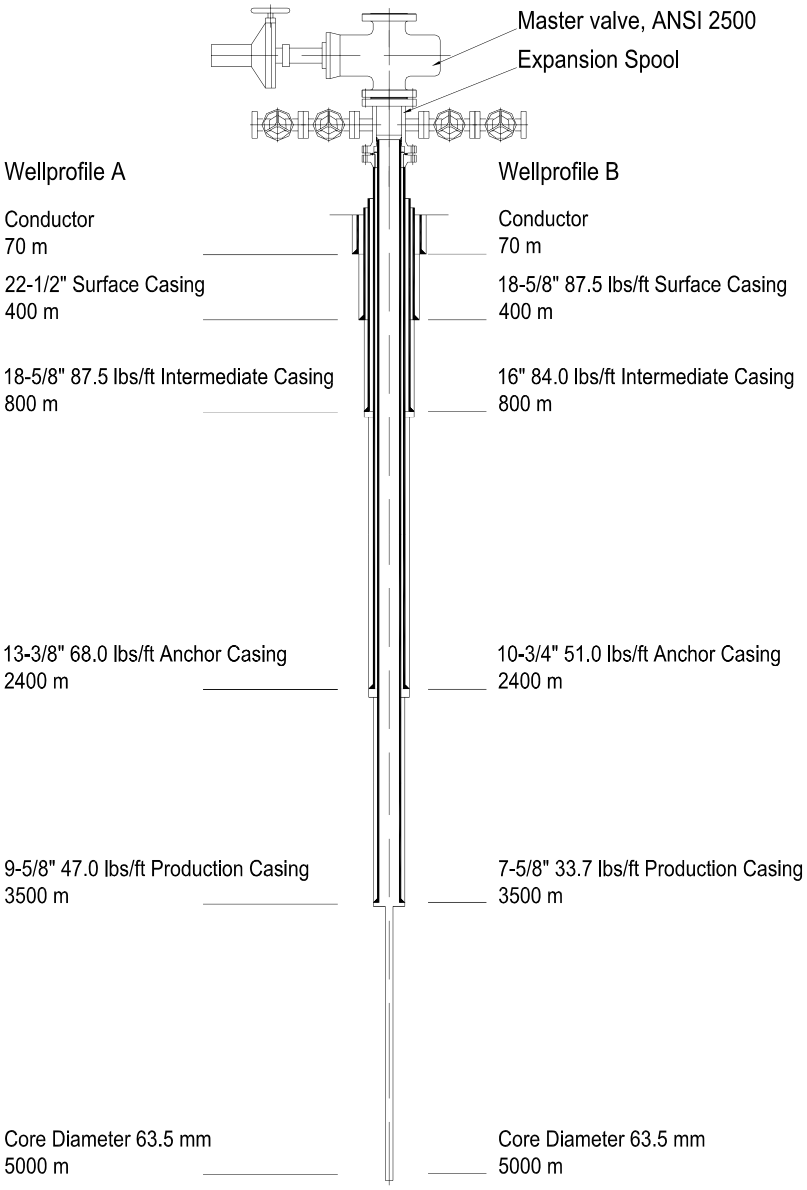


Figure 8.2 Casing program for well profile A and B

9. Casing Connections

Casing connection

Maruyama et al 1990 carried out what appears to be a extensive study of casing couplings for temperature as high as 354°C Their findings are that premium connections with metal-to-metal coupling seals provide excellent seal tightness in thermal wells at temperature up to the maximum testing temperature of 354°C (670°F). Further it was observed that the seal integrity of premium connections can be enhanced by use of coupling that are thicker and/or of higher-grade material than the pin and by using couplings made of quenched-and-tempered steel containing molybdenum. In the same study finds the sealing limits of API BTC to be 200°C (392°C) and API LTC of 300°C (572°F).

Based on this findings premium connections with metal-to-metal coupling seals is foreseen to be used for the project with enhanced coupling of couplings made of quenched-and-tempered steel containing molybdenum.

Figure 9.1 Premium connections with metal-to-metal coupling seals (Dalmine)

Premium connections for high-temperature service. Maruyama et al. (1990)
Because the high-temperature leak resistance of the premium connections results from the contact pressure in the metal-to-metal seal portion of the connection, the connection's performance can be enhanced by maintaining or increasing the contact pressure. Two methods can be used to maintain or increase contact pressure. The first method uses a stronger coupling; the second modifies the coupling material to minimize the adverse effect of stress relaxation. Grade C95 material that contained 0,45 molybdenum, however, showed very little reduction in seal diameter. Therefore, this material has good resistance to stress relaxation and would be a good material for premium connections.

10. Alternative well of 4000 m

The anchor casing design conditions for a 4000 m well are, based on the same temperature and pressure gradient below the CP at 3500 m as for 5000 m deep well.

Table 9.1 Design loads for 4000 m well

		Pressure	Temperature
		MPa	°C
Bottom hole conditions		23	433
At Well-head			
	Flowing Conditions	16	360
	Saturated Steam Column	18,5	359
	Empty well	23	20

The results of long-time creep calculation are carried out for 9-5/8”, 7-5/8”, 7” and 5” anchor casing at well-head casing. The results as listed in Table 9.2 Material and wall thickness of anchor casing for well-head conditions.

Table 9.2 Material and wall thickness of anchor casing for well-head conditions.

Nominal outside diameter	Nominal weight	Nominal wall thickness	Material	Calculated wall thickness
inc	lbs/ft	mm	API	mm
9-5/8”	47,0	11,99	K-55	11,9
7-5/8”	33,7	10,92	K-55	9,2
7”	26,0	9,19	K-55	8,6
5	18	9,19	K-55	5,8

The calculations show that K-55 is sufficient for the top part of the anchor casing in a 4000 m deep well.

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Iceland Deep Drilling Project

PART III

Fluid Handling and Evaluation

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SUMMARY

The properties of the fluids from the IDDP well will be evaluated in two stages. The first of these is a flow test through a narrow, replaceable liner or pipe inserted into the well. This pipe will serve to protect the casing and wellbore from corrosion and scale deposition during initial testing. This is particularly important if the fluids turn out to be hostile.

If the results obtained at this first stage are deemed encouraging, a wellhead pilot plant will be designed and constructed. Such a plant would constitute the second stage of the evaluation program. Since the temperature, pressure, and chemical composition of the well fluids are unknown, the design of such a wellhead pilot plant, even a preliminary one, is considered premature at this time.

Inserting a flow-test liner into the IDDP well is considered feasible. For this scheme to work, a downhole valve must be emplaced at the bottom of the cased section of the well, where the narrower, cored part begins. To this end, it is highly desirable that the casing be at least 9-5/8" in diameter. Temperature and pressure gauges will be installed along the entire length of the liner.

The downhole valve is an important component of the liner assembly. Although such valves are commercially available, none of these are made of materials that will withstand the high temperatures expected in this project. The downhole valve will thus call for development work, and so will the temperature and pressure gauges.

Producing an initially supercritical geothermal fluid through a 4" pipe, from a depth of 5000 m to the surface, is considered possible, provided the flow can been initiated. The fluid thus produced is unlikely to be supercritical at the wellhead, since this would require very high reservoir pressures and temperatures. For the fluid to be superheated at the wellhead, albeit not supercritical, the reservoir temperature at 5000 m must exceed 420 °C or so. Lower reservoir temperatures will cause the fluid at the surface to be two-phase. In this case the water fraction will be quite large if the reservoir pressure is high.

The reservoir temperature at 5000 m must be higher than 450 °C if the enthalpy of the fluid at the wellhead is to exceed that of steam produced by conventional geothermal wells. A deep well tapping a reservoir at a temperature lower than 450 °C would offer no particular advantage for electric power production over, say, a 2000 m well drilled into a 300 °C reservoir.

A deep well producing from a reservoir with a temperature significantly above 450 °C might, under favorable conditions, yield enough high-enthalpy steam to generate 40 - 50 MW of electric power. This exceeds, by an order of magnitude, the power typically obtained from a conventional geothermal well.

The steam from a high-temperature, high-pressure deep well will not be used directly to drive a turbine. Instead, a binary cycle of some kind will be chosen for power generation. The pressure of steam produced by the IDDP well(s) is thus not an important variable for this application. For some industrial processes, however, steam at a pressure of 40 – 80 bar_a is worth at least 7 - 8 USD/MT, at least twice as much as steam at 10 bar_a.

Extraction of chemicals from thermal fluids is unlikely to be economically feasible. This conclusion rests on the assumption that the fluid composition in the IDDP well(s) will not differ greatly from that of Icelandic wells drilled to date. Should the concentrations of valuable chemicals in fluids from the proposed deep well turn out to be significantly higher, however, the possibility of recovering these will be reconsidered.

The dilute fluids expected in the Krafla and Nesjavellir fields are less likely to present problems during flow testing and production than the more saline fluids expected in Reykjanes. From the standpoint of initial production and process development, it would thus be desirable if the first deep well were drilled in either Krafla or Nesjavellir. For purposes of chemical recovery, the Reykjanes site is, of course, much more interesting. One would hope to see all three sites drilled in due course.

The cost of installing the flow-test liner and operating it for a period of six months is estimated to be 425.2 million ISK.

CONTENTS

TABLES

FIGURES

1 OVERVIEW

When contemplating the initial production of a geothermal fluid of unknown chemical composition from a well drilled into an unfamiliar environment, one is presented with a dilemma. On the one hand, fluid must be extracted from the well for some period of time, even if only on a pilot scale, in order that its properties may be studied and an appropriate energy extraction process found. This very production may, on the other hand, result in permanent damage to the well, either because of corrosion of the casing, or because of solid deposition in the aquifer or the wellbore. This was one of the problems facing the working groups of the Iceland Deep Drilling Project (IDDP) at the first meeting in June of 2001.

At this meeting, there emerged a concept that soon came to be known simply as the "Pipe." This approach to flow testing involves inserting into the well a narrow liner, maybe 4" or so in diameter, all the way down to the production aquifer. The fluid will be extracted through the liner, which thus serves to protect the wellbore and the casing from the effects of the fluid. The liner may be removed and replaced if serious scaling or corrosion problems arise.

Confining the fluid to a tube of uniform diameter should also help maintain its upward flow. In the absence of such a liner, the fluid velocity might be reduced to an unacceptably low value in the wider casings found in the upper part of the well.

Although its primary function is protection, the pipe can be made to play an important additional role. After some appropriate period of production, the liner may be removed and inspected, section by section. Such a direct study of the pipe should yield information on corrosion and scale formation over the entire range of temperature, pressure, and fluid phase conditions obtaining in the well, provided, of course, that these properties are known as functions of depth. In this way, the pipe may be thought of as constituting the first phase of a pilot plant.

2 SCOPE

Any program of study involving the operation of the pipe must include, as a minimum, the following.

- The flow through the pipe will be monitored continuously at the wellhead. The cumulative amount of fluid carried by the pipe must be known if any sense is to be made of the extent of corrosion and scaling in the pipe.
- The temperature and pressure in the pipe will be monitored at certain depth intervals over a range of different flow rates. This is necessary to provide a reference, against which computations of the temperature and pressure profiles in the well can be checked.
- Coupons will be placed inside the pipe in order to investigate the corrosion resistance of prospective power plant materials.
- The chemical composition of the fluid emerging at the wellhead will be determined over a range of operating conditions.
- When the pipe is taken out of the well, any scale present will be removed from the liner, weighed, and analyzed. This will provide a quantitative measure of the scaling potential of various minerals over a range of thermodynamic and flow conditions.

3 FLOW THROUGH THE PIPE

The concept of inserting a narrow, removable liner into a deep geothermal well offers the promise of protecting the casing from corrosion, and the wellbore from scaling, during flow testing. The scheme nevertheless raises a number of questions.

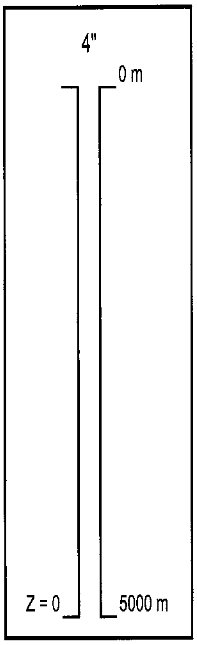
Can the fluid be produced through the pipe at all? In other words, will a steady flow of fluid through the liner, from a depth of 5000 m, sustain itself? Or will the pressure drop in the pipe conspire with heat loss from the fluid to the surrounding rock formation to kill the flow? And if the flow is sustainable, what will be the pressure, temperature, and the fluid enthalpy at the wellhead?

To address questions such as these, a computational model of the fluid flowing through the pipe was constructed. This wellbore simulator is described below, and the results of some calculations are presented.

3.1 Wellbore model

The fluid in the model is pure water, with no dissolved minerals or gases. This may seem like an odd choice, as it has been argued by some authorities that fluids in geothermal systems at supercritical temperatures and pressures are likely to be heavily mineralized.

Wellbore Model



$$dp/dz = -g\rho(T,p) - f(v,\rho,\eta,d)$$

$$T = T(p,h)$$

$$dh/dz = -g - (a/q)(T-T_{rock})$$

$$p_{in} = p_{5000}$$
$$T_{in} = T_{5000}$$
$$h_{in} = h(T_{5000},p_{5000})$$

p : pressure

T : temperature

h : specific enthalpy

ρ : density

v : velocity

η : viscosity

d : pipe diameter

f : Prandtl-Kármán function

q : mass flow rate

g : acceleration of gravity

z : height from well bottom

a : heat loss factor
(2.85 W m^{-1} K^{-1}
for 4" pipe at 4 weeks)

Figure 1. *Wellbore model.*

There are three reasons for choosing pure water as the working fluid in the model. The first is that such a calculation can be carried out with reasonable confidence, since the equation of state for water is accurately known to at least 800°C and 1 kbar. Such is not the case for a general aqueous fluid. Secondly, many Icelandic geologists are convinced that, because of the extensional tectonics of the country, there will be sufficient permeability and vertical circulation to keep the fluid reasonably dilute at depth, at least in the freshwater systems of Krafla and Nesjavellir. The third reason, and the most important one, is that pure water represents a limiting example, a best-case scenario. If this case appears promising, fluid production from the well for power generation should merit further study; if not, the well might reasonably be redefined as a coring well for research purposes only.

The salient features of the computational model are shown in Figure 1. The fluid enters a pipe, with a nominal diameter of 4" and an exact inner diameter of 100 mm, at a depth of 5000 m and rises towards the surface. As it ascends, the pressure drops because of the decreasing weight of the column above and because of friction in the pipe. At the same time, heat is lost by conduction from the fluid to the formation surrounding the well.

The governing equation of the wellbore simulator is the rate of change of pressure with depth. This rate is described by two terms. The first is the contribution of gravity, essentially the weight of water at some given point in the column. The second term represents frictional losses in the pipe and depends on the velocity of the fluid, its density and viscosity, as well as on the pipe diameter.

The rate of change of the fluid enthalpy with depth is also described by two terms. The first of these accounts for the cost of moving the fluid up against the force of gravity. The second term describes the loss of heat to the surrounding formation. This heat loss can be evaluated by solving the diffusion equation in a cylindrical geometry. The solution to this problem, and many others, may be found in the near-encyclopedic compendium of Carslaw and Jaeger: Diffusion of Heat in Solids. Although it is a time-dependent quantity, the heat loss factor, a, does not vary much for real wells. Its value is about 2.85 W m^{-1} K^{-1} for a 4" well that has been producing for four weeks, and 2.56 W m^{-1} K^{-1} for a 9" well that has produced for one year. These numbers were computed on the basis of typical bulk values for the properties of Icelandic basalts: a density of 2600 kg m^{-3}, a thermal conductivity of 1.7 W m^{-1} K^{-1}, and a specific heat of 900 J kg^{-1} K^{-1}.

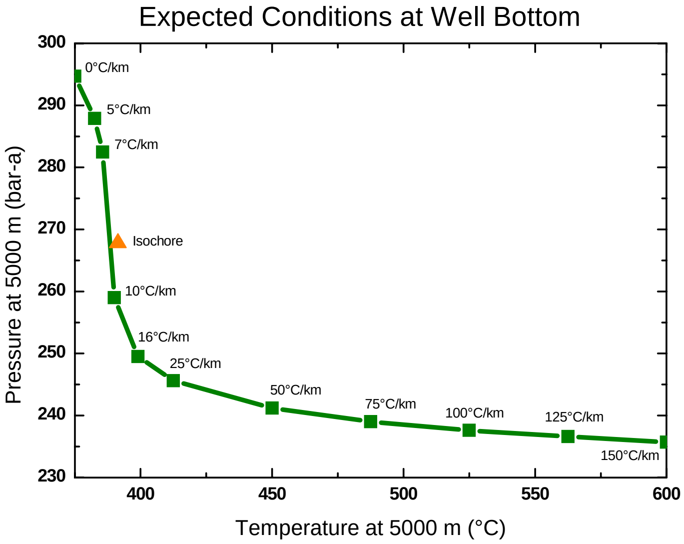


Figure 2. *Expected conditions at well bottom.*

These equations are integrated in a stepwise fashion at intervals of 1 m. At every step of the calculation, the temperature is computed from the pressure and the enthalpy at that point. For this purpose, the model relies on equations for the thermodynamic properties of water and steam parametrized in 1967 by the International Formulation Committee of the Sixth International Conference on the Properties of Steam.

The initial conditions for the calculations are the temperature and pressure at 5000 m depth. These are not known, however, so some assumptions must be made. A common point of reference in the IDDP discussions has been to assume that the fluid temperature and pressure follow the boiling point curve to the critical point, which in this case would be at ca. 3400 - 3500 m. This assumption seems reasonable, since a large number of geothermal systems worldwide have been observed to follow this curve approximately. Below this depth, a constant temperature gradient may be assumed, between 0 °C km^{-1} and 150 °C km^{-1}. Figure 2 shows what the temperature and pressure would be at 5000 m under these assumptions. The triangle indicates the temperature and pressure at 5000 m if the system were assumed to follow an isochore from the critical point onwards.

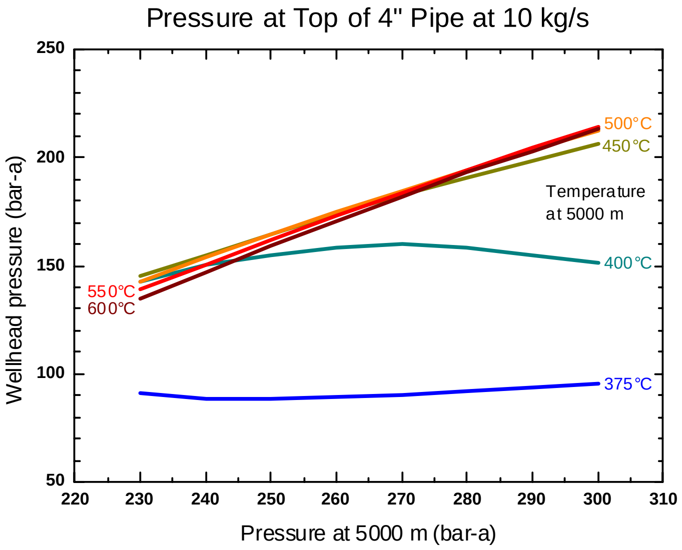


Figure 3. *Pressure at top of 4" pipe at 10 kg/s.*

Instead of limiting the calculations to this curve, it is instructive to cast a wider net and consider the entire region covered by Figure 2: temperatures from 375 °C to 600 °C, and pressures from 230 bar to 300 bar. Accordingly, numerous pairs of temperature-pressure values were chosen as initial conditions for the calculations, and a well profile was computed for each pair. The well profile includes values of temperature, pressure, fluid density, fluid enthalpy, fluid velocity, fluid viscosity, steam fraction, and heat loss as functions of depth in the well.

The temperature in the rock formation is assumed to trace the boiling point curve to the critical point, followed by a constant gradient down to the chosen temperature at 5000 m. This rock temperature profile is used to compute the heat loss.

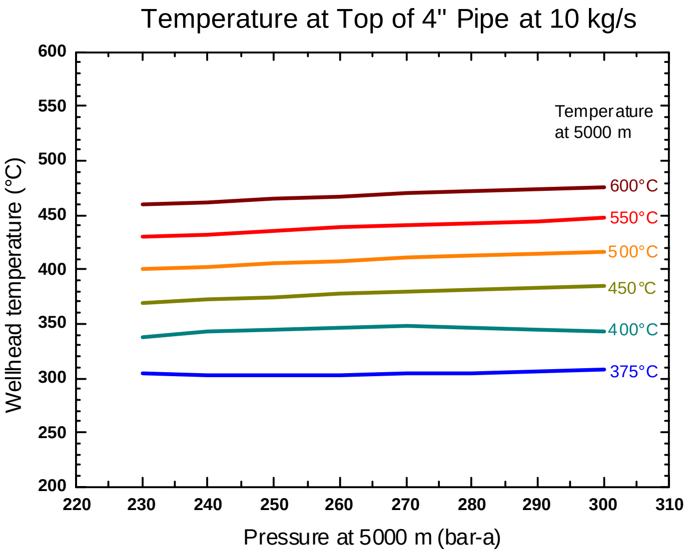


Figure 4. *Temperature at top of 4” pipe at 10 kg/s.*

3.2 Wellhead fluid properties

The wellhead fluid properties calculated in this way are presented in what follows.

At reservoir temperatures between 450 °C and 600 °C the wellhead pressure is virtually independent of the reservoir temperature, and roughly 90 bar lower than the reservoir pressure (Figure 3). At temperatures closer to the critical point, the wellhead pressure is sensitive to the reservoir temperature but almost independent of reservoir pressure.

The wellhead temperature is approximately 70 °C – 140 °C lower than the reservoir temperature and essentially independent of reservoir pressure (Figure 4). The relatively high wellhead temperature may have implications for the choice of valves and wellhead materials.

The enthalpy of the fluid will be higher than that of steam from conventional wells only if the reservoir temperature is 450 °C or higher (Figure 5). This value is not very sensitive to pressure.

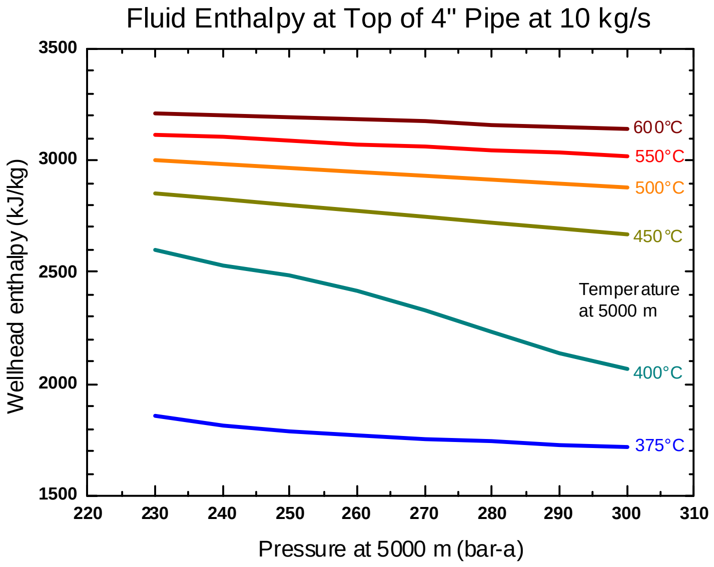


Figure 5. *Fluid enthalpy at top of 4” pipe at 10 kg/s.*

The heat loss from the pipe to the formation is significant, but not prohibitive (Figure 6). At high reservoir temperatures, the loss may amount to about 10% of the total enthalpy at a mass flow rate of 10 kg s^{-1} through a 4" pipe. The heat loss is not directly proportional to the mass flow rate. Thus, at a reservoir temperature of 600 °C, the heat loss is about 1000 kJ kg^{-1} if the flow rate is 2 kg s^{-1}, instead of the 1500 kJ kg^{-1} that a glance at the graph might lead one to expect. This is because the temperature in the upper part of the pipe falls with decreasing flow rate, and so the heat loss to the surroundings decreases correspondingly.

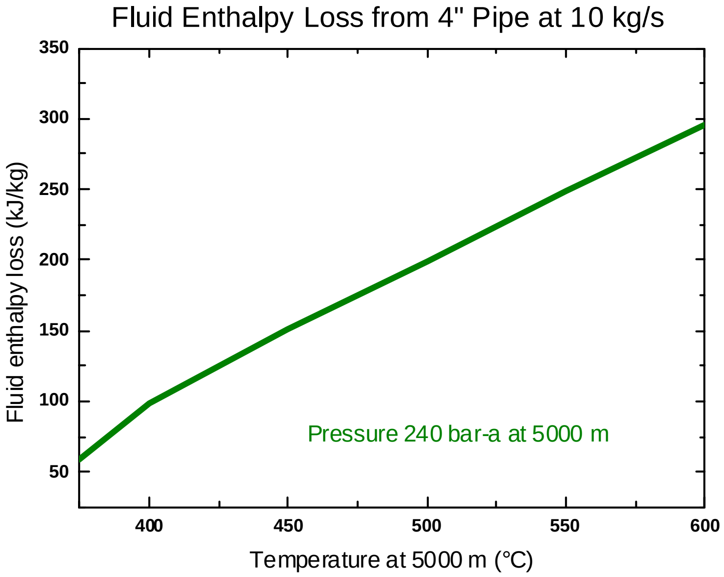


Figure 6. *Fluid enthalpy loss from 4” pipe at 10 kg/s.*

If the temperature at 5000 m is higher than about 405 °C at 230 bar, or higher than about 422 °C at 300 bar, the fluid produced will be superheated at the wellhead (Figure 7). At lower reservoir temperatures, a two-phase fluid will be produced at the surface. The water fraction of this fluid increases rapidly with decreasing reservoir temperature. It should be noted that the minimum reservoir temperature that will give rise to superheated steam at the wellhead is not very sensitive to pressure.

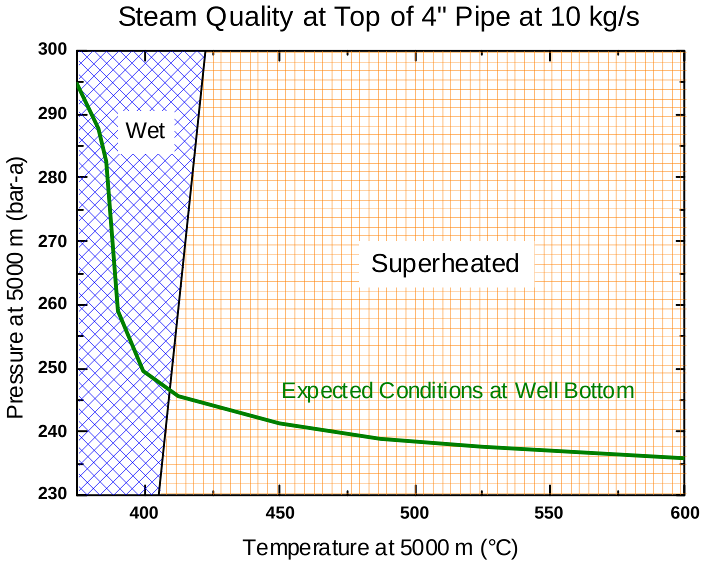


Figure 7. *Steam quality at top of 4” pipe at 10 kg/s.*

Clearly, the model can equally well be used to simulate production through a full-bore casing at high mass flow rates. A wider liner will result in less friction, and a higher flow rate will reduce the heat loss per unit mass. If fluids are produced through a 9" inner diameter casing at a rate of 50 kg/s, the threshold reservoir temperature for obtaining superheated steam at the wellhead drops by about 10 °C (Figure 8). If the reservoir temperature and pressure are high enough, the fluid may even be supercritical at the wellhead.

It should be kept in mind that all of the above analysis is based on the assumption that a steady flow of fluid through the pipe has already been established. Achieving this may not be trivial, however. Inductive heating of the pipe by means of an electrical coil has been suggested as a way of initiating the flow.

3.3 Main results

The salient results of the model calculations may be summed up as follows.

It is possible to produce initially supercritical geothermal fluid from a depth of 5000 m through a 4" liner, provided the flow can be initiated.

For the fluid produced to be superheated at the wellhead, the reservoir temperature at 5000 m depth must be higher than 420 °C or so. This value is rather insensitive to reservoir pressure and liner diameter.

The temperature at 5000 m must be higher than 450 °C if the enthalpy of the fluid at the wellhead is to exceed that of steam produced by conventional wells.

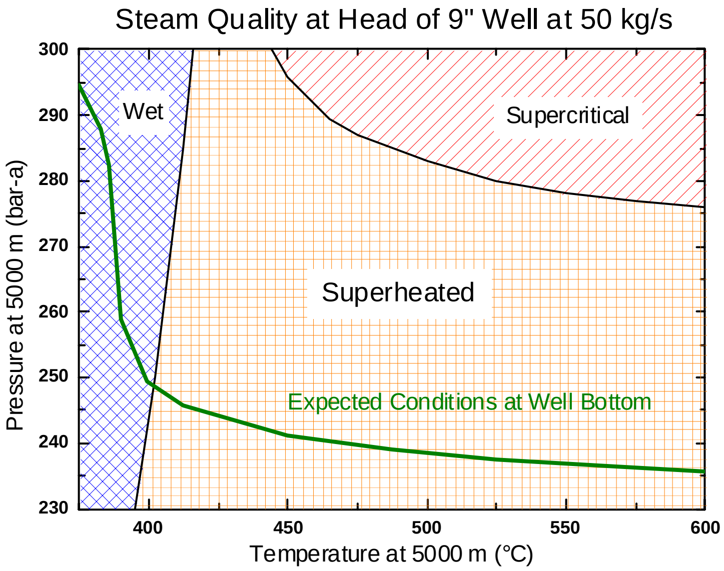


Figure 8. *Steam quality at head of 9" well at 50 kg/s.*

4 THE PIPE

4.1 Conceptual design

Figure 9 displays a schematic diagram of the pipe and the associated equipment. The pipe will extend from the wellhead all the way down to the bottom of the production casing, where a valve will be installed. The purpose of this valve is to keep the deeper, producing section of the well sealed off during periods when the pipe is not in place. This deeper part of the well will be left without a liner. The temperature and the pressure of the fluid in the pipe will be monitored by gauges placed at regular intervals.

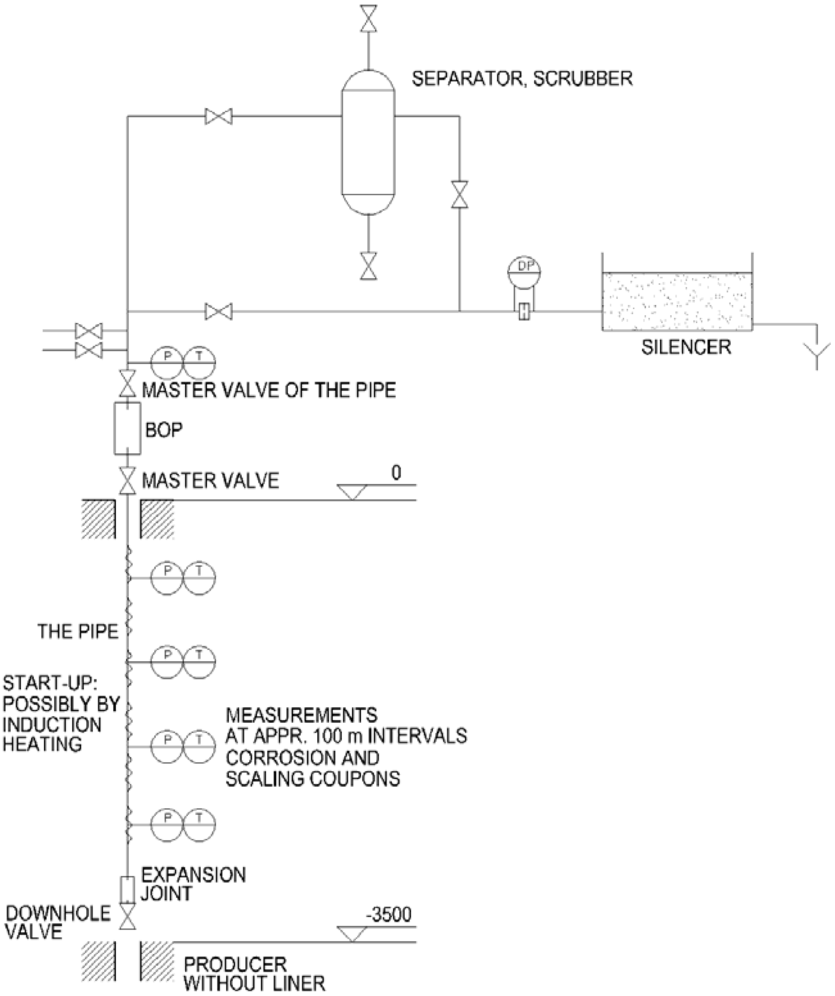


Figure 9. *A schematic diagram of the pipe.*

A paramount consideration is the safe operation of the well at all times. Careful attention must thus be given to the wellhead design. In particular, a blowout preventer must be in place for the duration of the fluid evaluation phase. Two master valves must also be installed, one on the anchor casing and another on the pipe itself.

Only relatively simple equipment will be required downstream of the wellhead during the initial fluid evaluation phase. A more sophisticated pilot plant may be constructed at a later stage.

4.1.1 Equipment downstream from the wellhead

Some equipment will be required to handle the fluid when it reaches the surface. This equipment, whose primary components comprise a separator, a silencer, and associated piping, must be designed to withstand temperatures of up to 500 °C and pressures of up to 250 bar. It must be resistant to both corrosion and erosion. The equipment will be used to:

- measure the rate of discharge of fluid from the well
- separate steam and liquid, or, if necessary, steam and solids
- collect fluid samples for chemical analysis
- deliver the fluid for disposal in an environmentally acceptable way

4.1.2 Blowout preventer

Blowout prevention equipment (BOP) should be installed on the wellhead. It should remain in place for the duration of the fluid evaluation phase, and indeed, as long as the pipe is in the well.

The BOP is identical to that used during the coring phase of the drilling. It consists of two pipe rams and a shear-blind. The pipe rams will close tightly around the pipe while the shear-blind cuts through the pipe. By closing the pipe rams, the well and the pipe can be operated even when the annulus between the well and the pipe is under pressure. The shear-blind is for emergency use.

The master valve of the well will be able to withstand a pressure of 260 bar at 500° C. This master valve, however, cannot be used when the pipe is running through it. Another master valve, also able to withstand 260 bar at 500 °C, will therefore be placed on top of the pipe. This valve will be used to shut off the flow through pipe, while other valves or orifices downstream will be used for flow control.

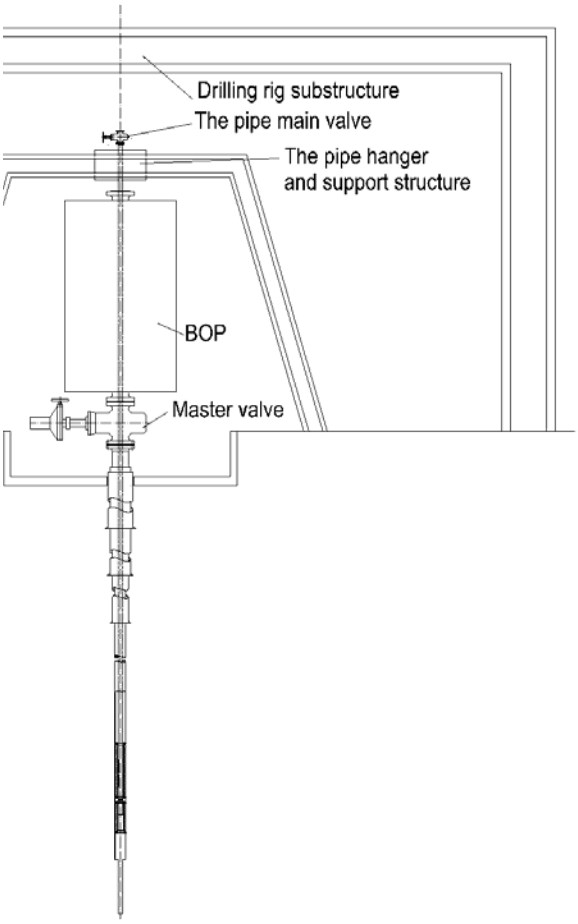


Figure 10. *The pipe, the wellhead and support structure.*

4.1.3 Hanger structure

The master valve and the BOP on top of it are quite heavy. A hanger structure above the wellhead is therefore necessary to carry this weight. The hanger structure will also support a platform from which the pipe head can be accessed. The hanger structure could be a part of a drilling rig substructure, which would be on top of the well during the fluid evaluation phase.

4.1.4 Flow initiation

The temperature of the pipe will presumably approach the temperature of the surrounding formation soon after it is installed. This temperature is much lower than that of a flowing well, especially near the surface. As a result, the well may not start discharging fluid without some sort of stimulation or flow initiation. Heating the pipe would help accomplish this. This heating can be achieved by electrical induction.

4.1.5 Downhole valve

A downhole valve installed at the bottom of the casing will facilitate the operation of the pipe. This valve will be open only when the pipe is in the well. Its purpose is to isolate the cased part of the well from the deeper section. The valve will be operated by a "stinger" on the end of the pipe. The stinger will open the valve as the pipe is installed. The end of the pipe will jut down through the valve, allowing room for thermal expansion of the pipe. When the pipe is removed, the stinger will close the valve as the pipe passes through.

The design of the downhole valve for the IDDP well might be similar to that shown in Figure 11, which depicts a valve produced by Halliburton. Their valve is, however, not designed for the extreme conditions expected in this well. While pressure should not be a problem, higher-temperature materials must probably be selected for the present project. One disadvantage of the Halliburton downhole valve is that a casing diameter of 9-5/8" is required for a 4.6" bore in the ball. In order to ensure sufficient anchor the valve must be placed at least 50 m up in the casing.

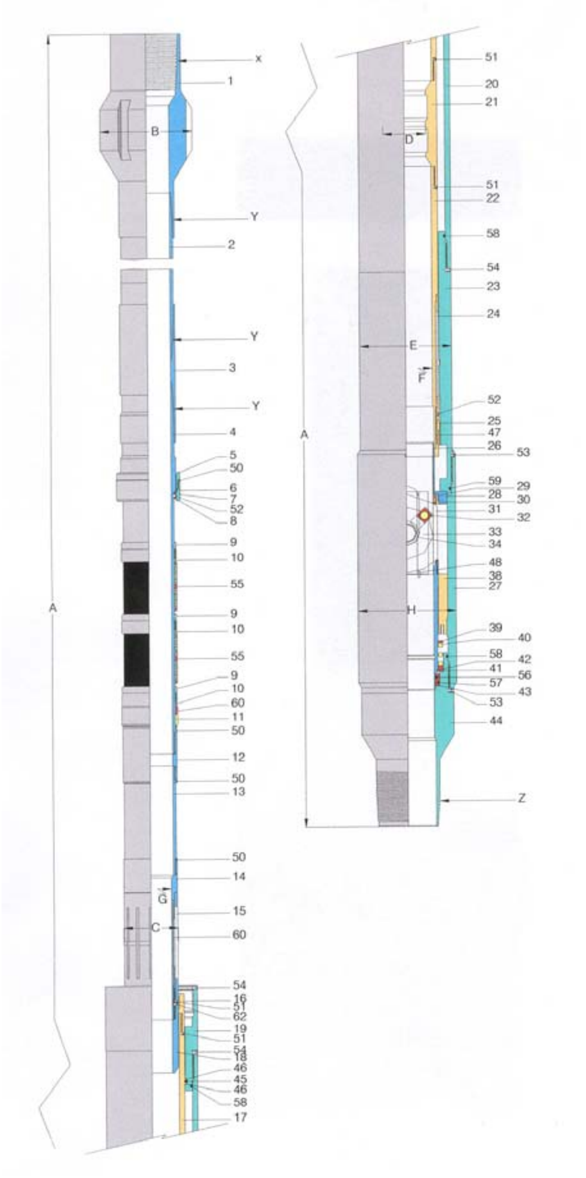
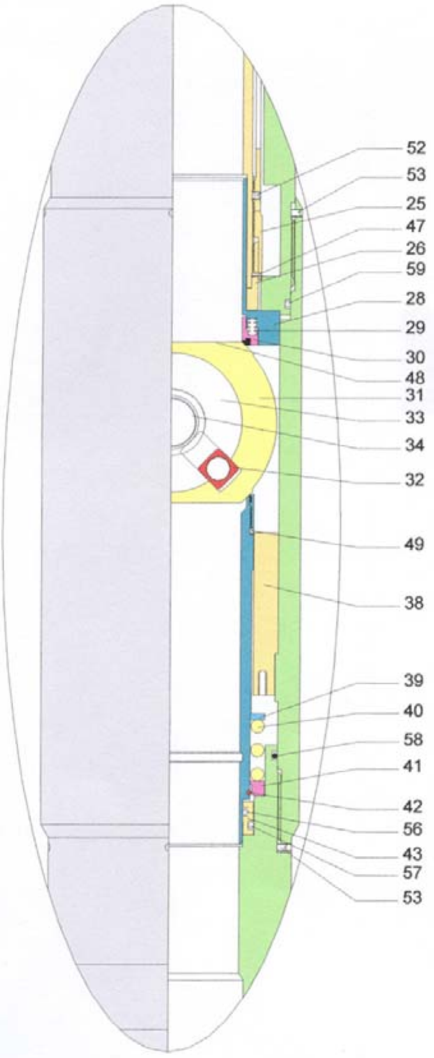


Figure 11. *Downhole valve made by Halliburton.*



Detail A

DIMENSIONAL DATA (Inches)	
A	393.47
B	8.000
C	4.750
D	3.730
E	7.994
F	4.600
G	3.600
H	8.500
Thread X	5-1/2" OD 17 lb/ft New Vam Box
Thread Y	4-1/2" OD 12.6 lb/ft New Vam
Thread Z	5-1/2" OD 17 lb/ft New Vam Pin

ITEM NO	QTY	PART DESCRIPTION
1	1	Crossover
2	1	Pup Joint
3	1	Coupling
4	1	Seal Mandrel
5	1	Shear Ring Retainer
6	1	20K Shear Ring
7	1	Shear Ring Housing
8	1	Shear Stub Retainer
9	3	Split Ring
10	3	Split Ring Retainer
11	1	Wiper Ring
12	1	Stinger Connector
13	1	Stinger Extension
14	1	Stinger Sub
15	1	Stinger Collet
16	1	No-Go Sub
17	1	No-Go Extension
18	1	Full Muleshoe
19	1	Top Sub Connector
20	1	Valve Connector
21	1	Shifting Sub
22	1	Piston Mandrel
23	1	Collet Housing
24	1	Collet
25	1	Ball Arm Connector
26	1	Ball Control Arms
27	1	Ball Housing
28	1	Ball Wiper Housing
29	6	Ball Wiper Spring
30	1	Wiper Seal Sub Ass
31	1	Ball
32	2	Ball Arm Bush
33	2	Trunnion Plate
34	2	Trunnion Bearing
35	0	Not Required
36	0	Not Required
37	0	Not Required
38	1	Lower Trun. Plate Supp
39	1	Spring Washer
40	1	Seat Spring
41	1	Lower Seal Load Ring
42	1	Snap Ring
43	1	Ball Seat Seal Carrier
44	1	Bottom Sub
45	1	T-Seal
46	2	T-Seal Back-up
47	4	Hex Soc. Set Screw
48	8	Dowel Pin
49	0	Not Required
50	8	Soc. Head Set Screw
51	6	Soc. Head Set Screw
52	14	Soc. Head Set Screw
53	6	Soc. Head Set Screw
54	6	Soc. Head Set Screw
55	2	4.875" VT Seal Head
56	1	O-Ring
57	1	O-Ring
58	3	O-Ring
59	1	O-Ring
60	1	Bearing Ring
61	1	Intensifier Collet
62	2	Soc. Head Set Screw

Figure 12. *Downhole valve made by Halliburton, list of items.*

The downhole valve could also be used during the coring of the deeper part of the well. This, however, is contingent on the size of the bore in the ball valve being large enough to admit the technical casing used during coring.

4.1.6 Expansion sleeve

The pipe will be approximately 3500 m in length. Heating this entire liner from a surface temperature of 5 °C to 500 °C would cause it to expand by around 20 m. This is not a realistic scenario, however. During installation, the pipe will be heated gradually. Furthermore, the temperature of the rising fluid decreases as explained in chapter 3. It is thus unlikely that the thermal expansion will exceed 10 m. The weight of the pipe will be supported from the top, and the expansion will be downwards through the downhole valve.

An expansion sleeve will be installed above the downhole valve. The sleeve, which will allow the pipe to expand, will seal the annulus between the pipe and the casing from the high-temperature fluid. The seal must be able to withstand a differential pressure of 250 bar at 500 °C.

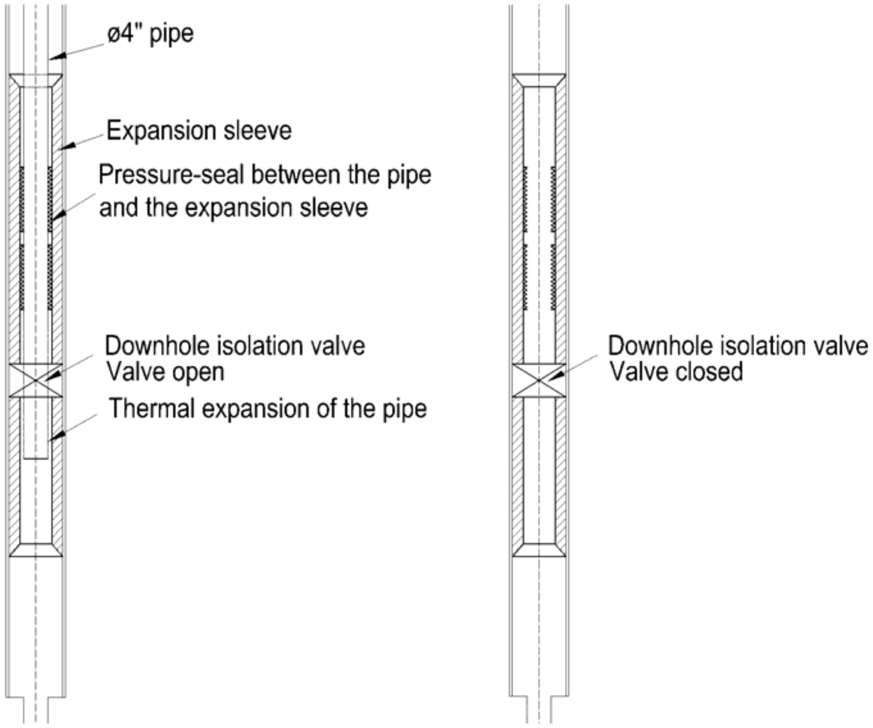


Figure 13. *Downhole valve and thermal expansion sleeve.*

4.1.7 Material selection

One part of the evaluation program is to determine the corrosion properties of the fluid. To this end, various materials will tested for corrosion in the fluid stream. This may be accomplished by constructing individual sections of the pipe of the different materials to be tested and by installing corrosion and scaling coupons in the pipe.

4.2 Measurements

The temperatures in the well are expected to exceed the operating temperature limits of commercially available electronic equipment. As a result, all amplifying and measuring devices must be lodged on the surface, outside the well. Cooling such equipment inside the well is considered neither reliable nor even feasible.

Probes are available for the measurement of temperature and pressure in the ranges expected. These employ proven technologies, and they must be wired to electronic equipment on the surface.

The space between the pipe and the inside of the casing limits the amount of wiring that can be accommodated. Figure 14 shows the estimated number of measuring points that will fit into the annulus between a 4" pipe and the casing, for several casing diameters. If a reasonably detailed temperature-pressure profile is desired, a 9-5/8" casing is clearly the preferred selection.

The following equipment is commercially available:

- For temperature measurement: Type Pt100 temperature sensors or thermocouples, screwed into spot-welded sockets
- For pressure measurement: Piezo-electric pressure sensors, screwed into the pipe wall
- For signal transmission: Solid metal-sheathed high-temperature wiring

A spectroscopic method of temperature measurement using fiber optic technology has also been considered. So far, this method has not been adapted to high temperatures, and development work is still needed. A drawback of this method is that any hydrogen gas present in the well will damage the fiber optic cable and shorten its lifetime.

Surface equipment at the wellhead will be used to determine the rate of discharge from the well. The flow will be measured with a venturi tube or an orifice meter after separation.

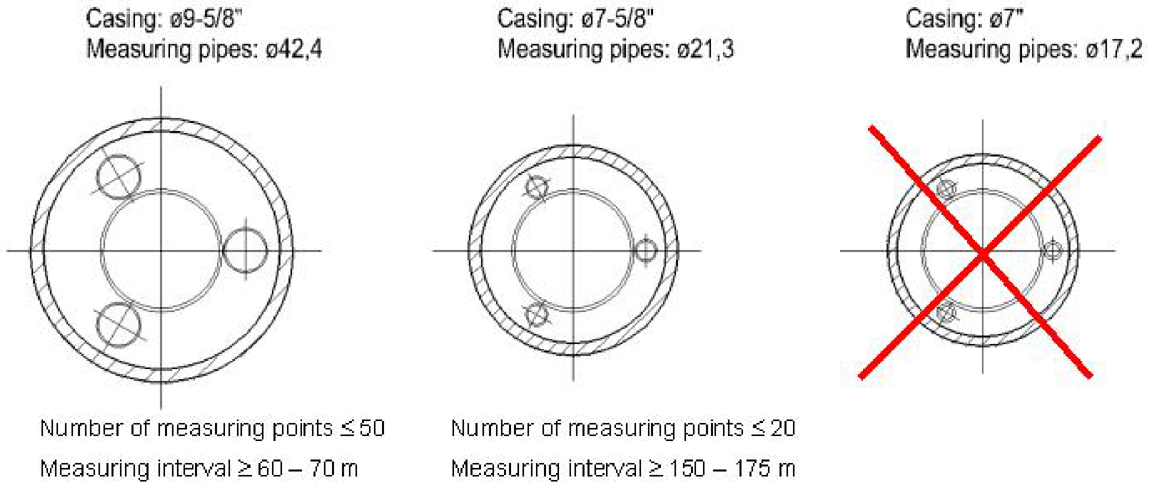


Figure 14. *A section through the production casing and the pipe.*

The measuring equipment needs to be calibrated prior to the flow test. One way of calibrating the pressure sensors is to fill the pipe with compressed gas and then compare the readings from the sensors with the applied pressure. The temperature may be calibrated by comparing the temperature reading of each sensor with the temperature measured by a logging tool at the corresponding depth.

4.3 Installation and replacement of the pipe

A major task in the fluid evaluation program is the installation, removal, and possibly, replacement of the pipe. Two ways of doing this have been considered. One is to employ a drilling rig positioned on the well. The other is to use a coiled tubing system.

4.3.1 Drilling rig

The drilling rig used for installing and maintaining the pipe need not be as large as the rig used for drilling the well. The weight of the pipe will be less than 55 metric tons, and the rig can be selected accordingly. The pipe would be installed in sections ranging in length from 10 to 30 m, depending on the size of the rig. The drilling rig provides the best means for solving any problems that might arise, for instance if the well must be plugged or killed, or if the pipe must be fished. Since the pipe must be installed and removed in sections, it will be difficult to replace under pressure, which may become necessary if the downhole valve fails. Should such a situation arise, the pipe must be plugged, or the well killed.

It may be of interest to collect downhole fluid samples during the evaluation phase. The lifting gear of the rig may be required for operating the downhole sampler.

4.3.2 Coiled tubing system

A coiled tubing system would comprise a drum of adequate diameter for the pipe, a unit for straightening the pipe, a driving mechanism, and a control system. Among the advantages of the coiled tubing system is its simplicity of operation and consequently low cost. A disadvantage is that the coiled tubing system is less suitable than the drilling rig for solving problems that may arise. Another disadvantage is that the plastic bending of the pipe, as it is removed from the well, may break up the scale inside the pipe, to the detriment of the fluid evaluation study. If the pipe is corroded, bending it on the drum without breaking it may prove difficult.

5 POWER GENERATION

5.1 Thermodynamic properties

The high-temperature fluid expected from the IDDP well offers two advantages for electric power generation over the fluid discharged from conventional wells. The first of these is the high enthalpy content, which promises high power output per unit mass. The second is the high pressure, which keeps the specific volume of the fluid small, allowing one to expect high mass flow rates.

Figure 15 shows the enthalpy of steam as a function of temperature and pressure. The figure shows clearly that the enthalpy increases rapidly with rising temperature, but decreases somwhat with rising pressure. The shaded area in the figure indicates the most probable range of reservoir temperatures and pressures.

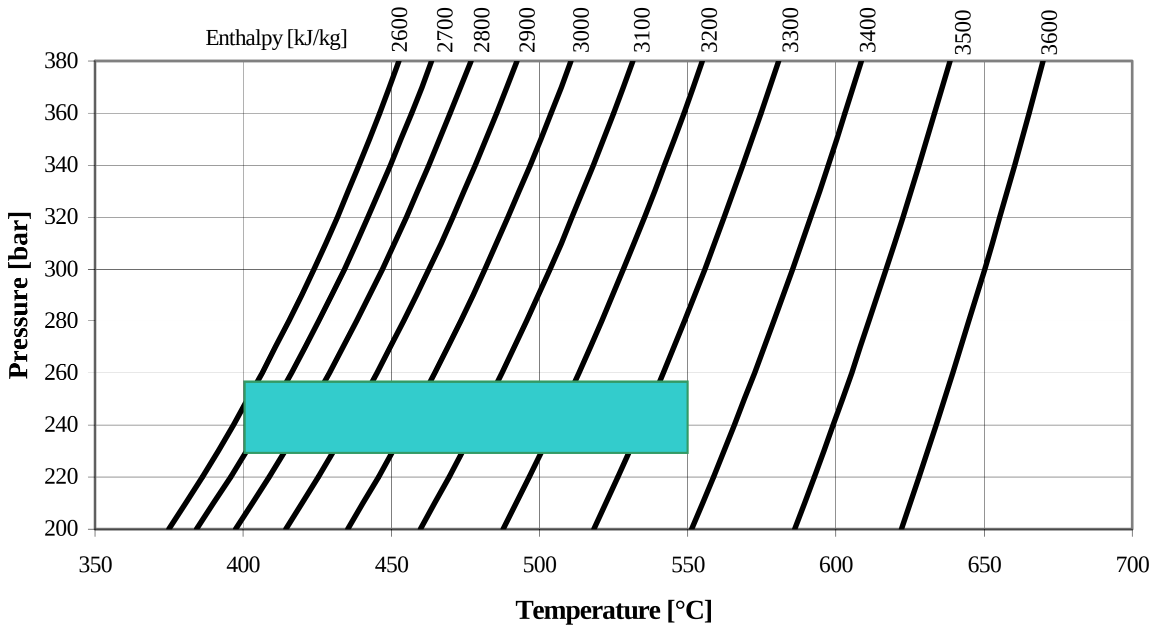


Figure 15. *Temperature, pressure, and enthalpy of supercritical steam.*

In what follows, the thermodynamic properties of the well fluids are assumed to be identical to those of pure steam, and the effects of any gases or minerals that may be present are ignored. This assumption was also made in Chapter 3.

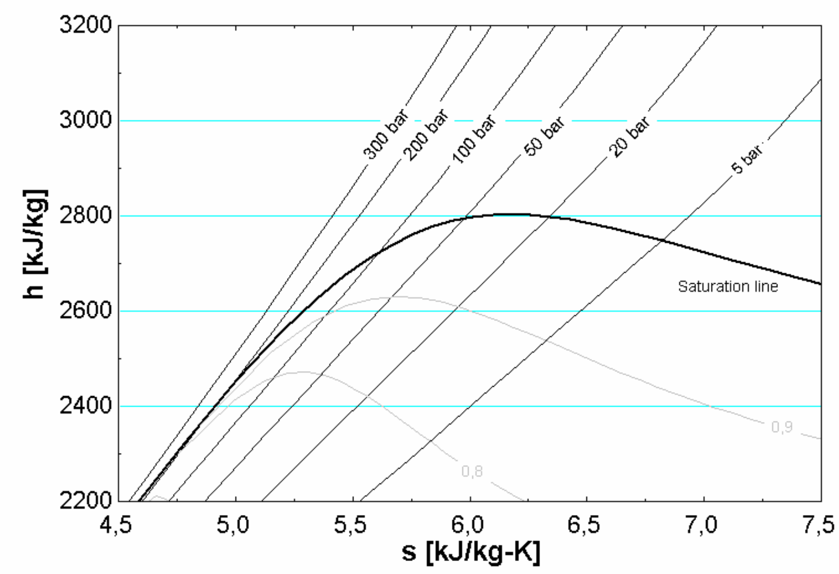


Figure 16. *Part of the Mollier diagram of water.*

A part of the Mollier diagram for water is shown in Figure 16. It is evident that if the fluid enthalpy is lower than about 2800 kJ kg^{-1} a liquid phase will form as the pressure drops at constant enthalpy. As pointed out in Chapter 3, the reservoir pressure must be at least 420 °C for the fluid to remain single-phase all the way to the surface. Two-pase flow in the well would reduce the wellhead pressure, and scaling problems might arise. Two-phase flow would also reduce the permissible fluid velocity and generally affect adversely the feasibility of using the fluid for electric power generation. Thus, if the fluid from the IDDP well is to be attractive for power generation purposes, its wellhead enthalpy should at least exceed 2800 kJ kg^{-1}.

5.2 Technology

The physical properties of the fluid will determine the choice of technology to be used for electric power generation. Until something is known about the fluid properties, little can be said about the process options available. It would nonetheless appear likely that the fluid will be used indirectly, in a binary system, as shown in the flow diagram in Figure 17. In such a process, the fluid from the well would be cooled and condensed in a heat exchanger, and then reinjected. This heat exchanger would act as an evaporator in a conventional closed power generating cycle.

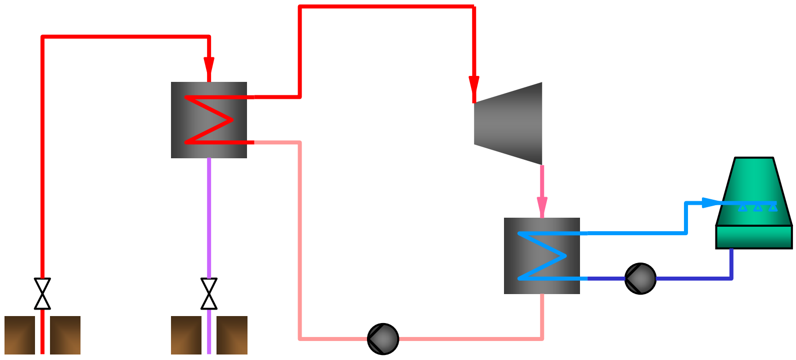


Figure 17. *Electrical production, indirect use of geothermal fluid.*

5.3 Comparison with Conventional Wells

In this section, the electric power that can be generated with fluids from an IDDP well tapping a supercritical reservoir will be compared to the power from a conventional geothermal well. The comparison is based on the following assumptions:

- The inflow to the conventional well is dry steam only
- The pressure at the wellhead of the conventional well is 25 bar_a and the pressure downhole is 30 bar_a
- The electric power generated by the steam from the conventional well is 5 MW
- The volumetric flow rate into both wells, the IDDP well and the conventional well, is the same, namely 0.67 $m^3 s^{-1}$

For simplicity, the conventional well used for reference is assumed to discharge dry steam only. Its assumed wellhead pressure is higher than that of typical geothermal wells in Iceland, so the comparison should be conservative in this respect. The downhole pressure of the reference well was computed on the basis of pressure drop and heat loss. Even though most conventional wells in Iceland produce a mixture of steam and water, this comparison, which is based on the same volumetric inflow, should be meaningful.

The flow diagram in Figure 18 presents a possible power generation cycle for the IDDP fluid, and Figure 19 displays a cycle for a conventional geothermal power plant. Figure 20 shows the electrical power generated by IDDP fluids in the above cycle as a function of reservoir temperature, for reservoir pressures of 230 and 260 bar. It should be noted that the calculated electric power output decreases with increasing reservoir temperature. The reason for this is the assumption of constant volumetric inflow. The specific volume of steam increases with temperature, reducing the mass flow rate as shown in the figure. Thus the calculated power output falls with rising temperature even though the enthalpy increases.

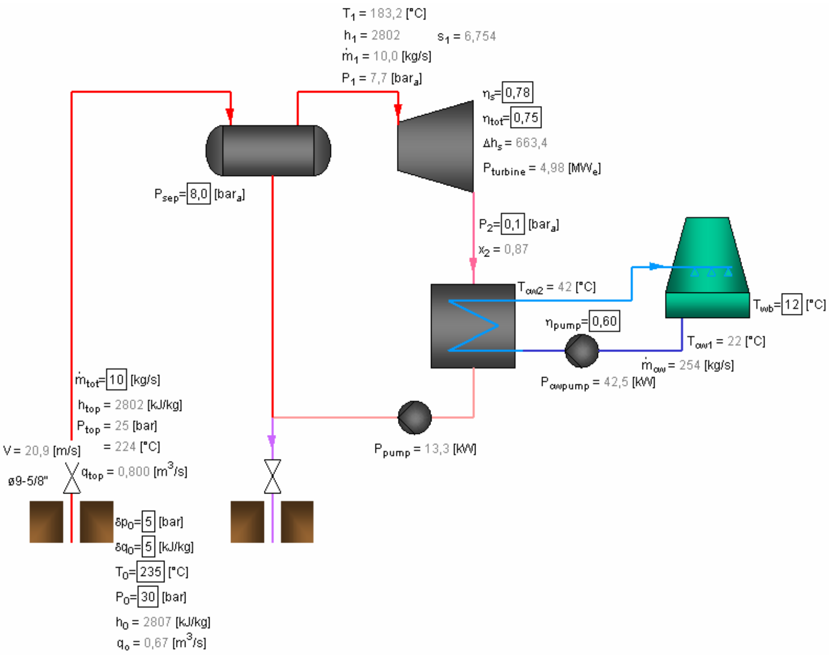


Figure 18. *Conventional geothermal power generation cycle.*

The primary conclusion to be drawn from these calculations is that under favorable conditions, i.e. if the temperature of the fluid from the IDDP well is high enough and if the volumetric inflow is similar to that of a conventional well, it may be possible to produce up to 50 MW of electric power from one well tapping a supercritical reservoir.

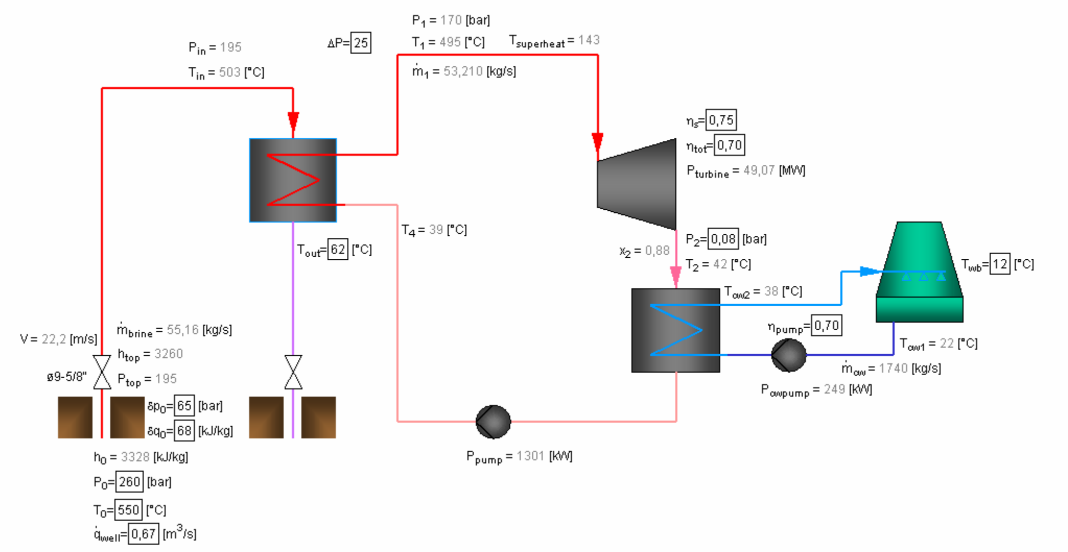


Figure 19. *Power generation cycle for high-temperature fluid.*

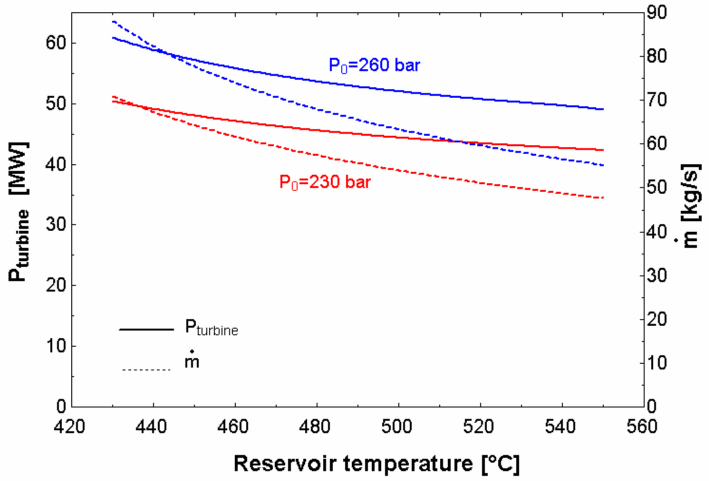


Figure 20. *Electrical power generated by fluid from the IDDP well. Flow rate of this fluid.*

6 CHEMICAL PRODUCTION

The high-temperature, high-pressure geothermal fluids expected from the proposed IDDP well, and from other similar wells, may be put to uses other than electric power generation. Three aspects, in particular, of their potential application to chemical processes have been considered.

The first of these is the extraction of minerals or gases from the fluids at the wellhead, by conventional means. Secondly, a concept involving the downhole shock-precipitaion of minerals has received some thought. A third possibility would be the use of the high-pressure steam in industrial processes for which conventional low-pressure geothermal steam is inadequate.

At this time, nothing is known about the chemical composition of fluids expected from the proposed IDDP well. Therefore, it seems most reasonable to assume that the compositon of the fluid in the deep reservoir of each field is similar to that of the composition at shallower levels. This assumption must be made for the purposes of the present study.

6.1 Chemical processes

6.1.1 Gases

Geothermal fluids invariably contain noncondensible gases in some concentrations. The major such gases found in fluids from Icelandic geothermal wells are carbon dioxide (CO_2), hydrogen sulfide (H_2S), and hydrogen (H_2). The fluids ordinarily also contain minor amounts of methane (CH_4), nitrogen (N_2), and argon (Ar). The relative concentrations of the individual gas components vary rather widely between fields, as does the total gas content. This is evident from Table 1.

Table 1. *Gas content and composition of geothermal steam from candidate fields.*

	Reykjanes	**Nesjavellir**	**Krafla**
Separator pressure	12.5 bar_a	12 bar_a	11 bar_a
Average gas content	0.5 % w/w	0.5 % w/w	1.5 % w/w
Carbon Dioxide, CO_2	4 500 mg/kg	3 200 mg/kg	9 450 mg/kg
Hydrogen Sulfide, H_2S	150 mg/kg	970 mg/kg	1 150 mg/kg
Hydrogen, H_2	0.35 mg/kg	50 mg/kg	29 mg/kg
Methane, CH_4	0.24 mg/kg	5 mg/kg	2 mg/kg
Nitrogen, N_2	20 mg/kg	340 mg/kg	22 mg/kg

A plant for the separation of carbon dioxide from geothermal steam was operated in Reykjanes for a brief period of time in the 1980's. The sulfide content of the gas made it unsuitable for use in the food and beverage industries without extensive, and expensive, purification. This spelled doom for the operation, since the food and beverage industries are the primary buyers of carbon dioxide in Iceland. The consumption of this gas by other industries is relatively modest. The concentration of hydrogen sulfide in steam is considerably higher in the Krafla and the Nesjavellir fields than in Reykjanes, which would make the separation of carbon dioxide even less attractive there.

A single geothermal well, located in the Grimsnes district, currently meets the industrial demand for carbon dioxide in Iceland. This well produces fairly pure CO_2, which requires little processing besides the removal of trace amounts of hydrogen sulfide.

The export of industrial grade CO_2 is uneconomical. The high transport cost of this low-priced commodity precludes any serious consideration of this option.

The recovery of carbon dioxide from IDDP well fluids is thus not considered economically feasible.

The hydrogen sulfide content is relatively low in steam from wells in the Reykjanes field, but considerably higher in Krafla and Nesjavellir. Reykjavik Energy has conducted a study comparing various technologies for the separation of hydrogen sulfide from the gas stream. Their study found that the capital and operating costs of any such process would be high compared to the potential revenue that might be expected from the production of either sulfur or sulfuric acid. The market for both in Iceland is small and declining. The supply of elemental sulfur on the international market is increasing, and prices are low. The supply of sulfuric acid is abundant. The production of these chemicals in Iceland might thus well incur costs resulting from their disposal.

New technologies for the splitting of H_2S into its elements are emerging. These may, in time, lead to processes for hydrogen sulfide utilization that are more economical than those presently available.

Of the three candidate fields, Nesjavellir displays the highest concentration of hydrogen in steam. At current production rates, the hydrogen emissions from this field total approximately 200 – 250 metric tons per year. Even though hydrogen is a valuable gas, this quantity is too small to support a hydrogen-consuming industry at the site, or to pipe over long distances. Burning the hydrogen would yield thermal power of approximately 1 MW, which is insuffient to justify investment in the necessary equipment.

The content of methane, nitrogen, and argon is very low in all the candidate fields. No realistic value can be assigned to any of these gases in these three geothermal fields.

The general conclusion is thus that some gases with commercial value can probably be separated from the expected IDDP well fluids. Under current conditions, however, no potential market can be seen for any of them.

6.1.2 Dissolved solids

Table 2 displays typical major element concentrations in geothermal water from wells in each of the three candidate fields. It should be pointed out that these are concentrations in the liquid phase after steam separation.

Table 3 similarly shows typical trace element concentrations in water in the three fields. Note that the concentrations here are expressed in μg/kg, a unit 1000 times smaller than that used in Table 2.

The total concentration of dissolved solids is relatively low in both Krafla and Nesjavellir fluids. Reykjavik Energy has conducted a prefeasibility study of the extraction of silica from Nesjavellir fluids. The results were disappointing. No other chemical of commercial value is found in a concentration high enough to support economical production.

The concentrations of almost all dissolved minerals are considerably higher in Reykjanes fluids than in geothermal fluids found elsewhere in Iceland. In particular, the Reykjanes fluids contain sodium, potassium, calcium, and chloride in substantial concentrations. Even so, a plant producing a low-sodium, high-potassium "health salt" from these fluids has failed to turn a profit under several owners. It is considered unlikely that any of the other elements present could be extracted economically.

Table 2. *Major element concentrations in geothermal water from steam/water separator [mg/kg].*

	Reykjanes	**Nesjavellir**	**Krafla**
Total dissolved solids	44 000	1 000	1 330
Silica (SiO_2)	870	807	574
Sodium (Na^+)	12 900	140	285
Potassium (K^+)	1 900	29	32
Calcium (Ca^{+2})	2 150	0.2	6.2
Magnesium (Mg^{+2})	1.0	0.005	0.04
Sulfate (SO_4^{-2})	20	8	307
Chloride (Cl^-)	25 400	106	40.5
Fluoride (F^-)	0.20	0.95	1.08
Iron (Fe)	0.7	0.05	0.08
Boron (B)	10		1.12
Aluminum (Al)	0.07	1.67	1.33
Hydrogen Sulfide (H_2S)		73	11.9
Carbonate (CO_3^{-2})		38	61.5

There are indications that the solubility of some elements may increase very rapidly at temperatures and pressures just above the critical point, in the range of target temperatures and pressures for the IDDP project. If this is so, then the decompression and cooling of the rising fluid may quickly deposit large amounts of scale in the pipe. During the preparation of this study there was insufficient information available on this subject to draw particular conclusions or to make firm recommendations. Even so, these indications suggest that downhole fluid samples should be collected from the deep well as early as possible.

Table 3. *Trace elements in geothermal fluid [µg/kg].*

	Reykjanes	Nesjavellir	Krafla
Zink (Zn)	26.5	1.94	1.52
Manganese (Mn)	3 600	3.8	1.97
Nickel (Ni)	1.7	0.123	0.19
Arsenic (As)	132	1.8-20.9	59.5
Mercury (Hg)	0.5	<0.0022-0.020	0.0039
Cadmium (Cd)	<0.03	<0.0050	<0.002
Lead (Pb)	<0.8	<0.030	0.0216
Copper (Cu)	0.9	<0.100	0.197
Cobalt (Co)	<0.1	<0.005	<0.005
Chromium (Cr)	n.i.	0.031	0.127
Barium (Ba)	n.i.	0.179	2.35
Molybdenum (Mo)	n.i.	0.374	3.44
Strontium (Sr)	n.i.	2.05	22

6.2 Solution mining

High-temperature geothermal fluids can mobilize large quantities of metals, particularly if the fluids are saline. This is most dramatically demonstrated by phenomena such as "black smokers" on the ocean floor. If the IDDP well fluids turn out to contain high concentrations of base or heavy metals, and particularly it these fluids turn out to be supercritical, an interesting opportunity may present itself.

The group conducting this study has received valuable suggestions from researchers at the University of Manitoba who have been working on novel methods of solution mining. They have suggested injecting cold water deep into the well to shock-precipitate minerals out of the fluids. The idea, in effect, is to create an artificial black smoker in the well. The precipitated minerals would be carried as a slurry to the surface by the rising geothermal fluid. The solids would then be separated from the fluid at the surface for further processing. The slurry would act as an abrasive during the ascent, helping to keep the bolehole or pipe wall free of scale. If this technology turns out to be successful, significant quantities of metals could be mined from solution. Much development work still remains to be done, however.

6.3 High-pressure geothermal steam

Geothermal steam in Iceland is usually separated from the liquid phase at pressures of 9-12 bar_a. In some instances, the steam is separated at a lower pressure, and occasionally a second separation stage is added at 1-3 bar_a. At any rate, the temperature of geothermally produced steam is typically in the range of 170-190 °C. Although adequate for turbine operation in electric power plants, this temperature imposes considerable constraints on the industrial utilization of the steam.

Many chemical industries require steam with a condensation temperature of 250-290 °C for various drying and distillation processes. The corresponding pressure is about 40 to 80 bar. Coal-fired water-tube boilers represent the most common way of producing such steam, whose cost does not vary much over this pressure range. A detailed steam cost estimate, done in 1996, yielded a value of 7.61 USD per metric ton (MT). Since that time, the price of coal has remained at approximately 30-33 USD/MT, so the minimum price of such high-pressure steam is still considered to be in the range of 7-8 USD/MT. In many places, both in Europe and in the United States, steam prices of 10-13 USD/MT can be expected. In countries in which a carbon dioxide emission tax is under consideration, a tax of 5-25 USD/MT of CO_2 has been proposed. Such a tax would add approximately 2-9 USD to the cost of each metric ton of steam.

The value of high-pressure steam from a successful IDDP is thus estimated to be in the range of 7-8 USD/MT. This is two to three times the value of conventionally produced geothermal steam.

Table 4. *Cost of steam from various sources.*

Steam source	Cost
Geothermal steam for power generation	2-3 USD/MT
Low cost HP steam from coal	7-8 USD/MT
Medium cost HP steam from coal	10-13 USD/MT
High cost steam from coal with CO_2 tax	12-20 USD/MT

7 COST ANALYSIS

The estimated cost of the fluid handling and evaluation program described in this report is presented in Table 5. The cost figures are given in millions of Icelandic kronas (MISK), exclusive of value added tax. The cost analysis is based on prices in January 2003.

Table 5. *Estimated cost of the fluid handling and evaluation program.*

Fixed Cost – Equipment					
Downhole valve	1	unit		25	25.0
Expansion joint	1	unit		10	10.0
The Pipe	3	unit		37	112.2
Pipe material	3500	m	0.003	11	
Downhole sensors	70	unit	0.15	11	
Cables, protection etc.	41	km	0.4	16	
Master valve of the pipe	1	unit		3	3.0
Wellhead	1	unit		12	12.0
Measuring equipment at wellhead	1	unit		5	5.0
Separator, silencer, etc	1	unit		25	25.0
Variable Cost					
Commissioning	10	days		0.5	5.0
BOP rental	180	days		0.2	36.0
Lifting equipment	60	days		0.5	30.0
Observation	180	days		0.08	14.4
Chemical analysis of liquid and gas	20	samples		0.125	2.5
Scale analysis	150	samples		0.1	15.0
Downhole sampler	40	days		0.5	20.0
Report	150	days		0.08	12.0
Subtotal					327.1
Contingent	30%				95.4
Total:					425.2