Iceland Deep Drilling Project (IDDP): The challenge of drilling and coring into 350-500°C hot geothermal systems and down to 5 km

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Abstract

The technology and engineering challenges of drilling and coring the proposed well for the Iceland Deep Drilling Project (IDDP) to 5 km have been evaluated. The results were published in a Feasibility Study (2003) and his paper is a short summary of the findings. In order to meet the major goals set by the project sponsors a "dual purpose" hole had to be designed to: a) allow fluid to be produced to meet the engineering goals of the power companies and b) meet the scientific goals by continuously coring the lower part of the hole where the very high temperatures are expected. Two wells were designed of different diameters. Top part of the anchor casing has to be from special creep resistant steel, but conventional API grade K-55 can be used for other casing strings. The greatest danger to the casing is thermal cycling, as the steel is stressed beyond the yield point due to limited thermal expansion. The risks in terms of blow outs and other geologic risks were addressed and it found coring to be most critical. Finally cost- and time estimates were prepared for the two wells. The cost was estimated to be US$ 14.4 – 15.5 million and taking 258-270 days. An alternative where existing wells would be cased to 2400 m and then cored to 4000 m was estimated to cost US$ 5.8 million.

Keywords: *geothermal drilling, geothermal well, deep drilling, scientific coring, supercritical fluid.*

1 Introduction

The goals for the IDDP well were set by a group of experts known as Science Application Group of Advisers (SAGA). The task of designing the well and proposing the drilling technology to be applied to meet these goals, was given to a group of Icelandic experts – the authors of this paper. They received extremely valuable assistance from drilling experts and scientists attending two ICDP sponsored workshops, especially in incorporating continuous coring into the project. Drilling down to 2500 m and into temperatures above 320°C is routine in Iceland but only spot cores have been taken in three high-temperature wells out of 120 drilled to date.

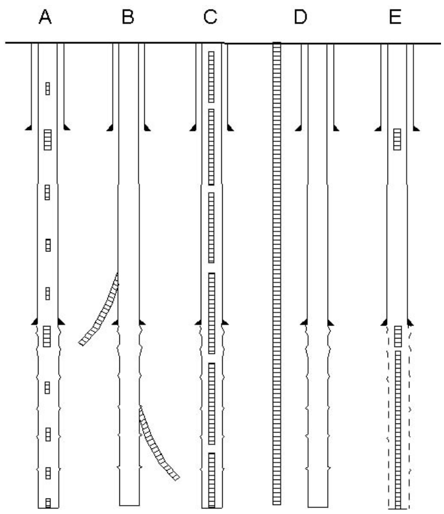

Figure 1: Coring strategies considered in SAGA 1 report.

The implications of the "add-on science" meant that cores would be required. In Figure 1 the alternative coring strategies identified at the SAGA meeting in June 2001 are depicted. The recommendation was alternative E, namely to core at casing points and continuously in the supercritical zone. Later the open hole could be increased in diameter by reaming, allowing more fluid to be produced. After IDDP's Workshop I, held in the spring of 2002, this was modified by the suggestion that continuous cores also be taken in the expected transition zone to supercritical for the depth interval 2400-3500 m.

2 Coring

One of the early tasks was to identify what core diameter would meet the science requirements and then to identify what coring equipment and technology to apply. These are the main coring systems considered (Bernd Wunders):

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

Experts with first hand knowledge presented three scientific coring systems employed to-day at Workshop I (Dennis Nielson and Marshall Pardey (US), Bernd Wunders (Ger.), Mikael Geldgaf (Rus.). Table 1 compares these three equipment options, falling under coring system alternatives C and D above, namely DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust), BRR and CCS. These have been used in past deep scientific drilling projects, but at significantly lower temperatures. They vary in the diameter of hole and of core and also in the type of drill string used. The rig set-up of drives (top-drives) and precision feeding required for coring is also somewhat different. Common to all is that they can be installed in conventional masts but require a top drive and feed control (precision lowering of the drill string).

Table 1: Comparison of different coring equipment options.

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" 2.4" 4.0"	8 1/2" 3 7/9" 6 3/4"	CCS DOSECC BRR	2.3-5.0 2.3-5.0 2.3-5.0	**op-3**
				2.6-3.1" 2.4" 4.0"	8 1/2" 3 7/9" 6 3/4"	CCS DOSECC BRR	3.4-5.0 3.4-5.0 3.4-5.0	**op-4**

The DOSECC Hybrid Coring System (DHCS) uses a small diameter "mining type" core barrel, type HQ, hole 3-7/9". This hole requires subsequent reaming to production size hole (e.g. 8-1/2"). The BRR "large diameter hole" size is 6-3/4" and CCS 8-1/2" which do not require reaming.

The feedback from the scientist at IDDP's Workshop II, held in the autumn of 2002, was that they would be able to use the smaller size core (DOSECC-DHCS). That equipment has been used in high-temperature drilling in Indonesia and most recently in Hawaii where the temperature was not high but the geology similar to Iceland's. The amount of information available on performance and cost influenced the selection of the DOSECC unit for this study.

The basic arrangement is to install a coring unit in the mast of a conventional rotary rig (Figure 2). This 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 DOSECC unit consists of a hydraulic top drive and a cylinder for precise feed control, has its own wireline winch and mud pumps and a power pack to run all the equipment. 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 drill rods are stronger than for normal diamond drilling (Table 2). Because of the small hole size a special “technical casing” (5”) has to be hung in the hole from surface during the coring phase to guide and support the coring string and allow fluid circulation. The drilling fluid is a water based polymer mud and the circulation rate is about 5 l/s. Return of mud to surface is not expected due to circulation losses. The blow out prevention equipment of the coring unit is a Kelly valve and a complete BOP stack. The unit has a depth rating of 6000 m and been used on several scientific coring projects down to 3000 m and at another location at temperatures to 340°C. The coring rate estimate is based on information from a well in Hawaii HSDP. For the IDDP cost estimate a penetration rate of 25 m/day is assumed to 3500 m and 20 m/day below that depth.

The sequence of drilling, reaming and coring is shown in Figure 3.

Table 2: Proposed DOSEDCC tapered drill string to core to 5000m. 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

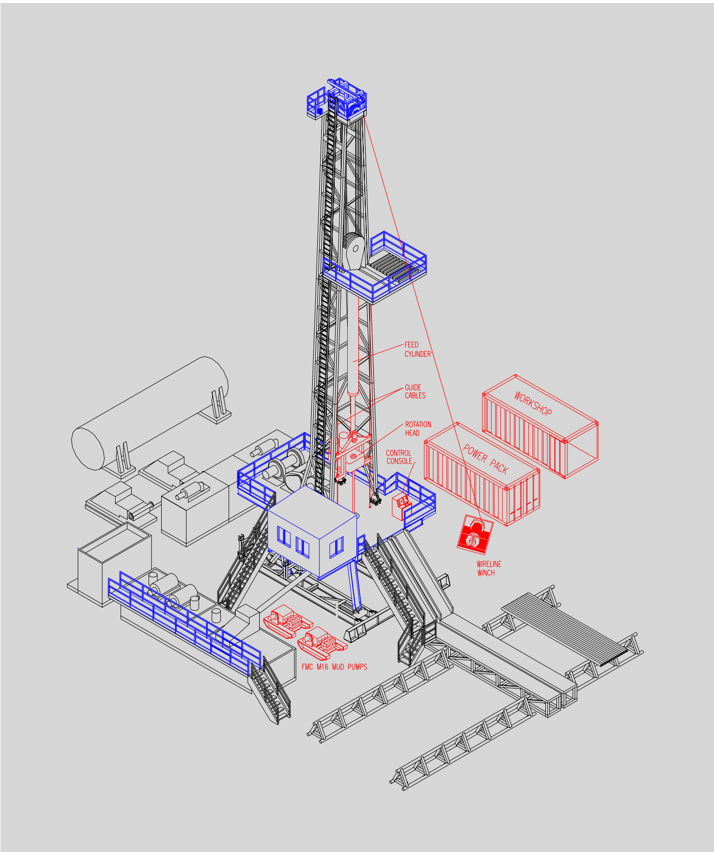

Figure 2: The DOSEDCC-DHCS coring system fitted to a conventional rig (DOSECC).

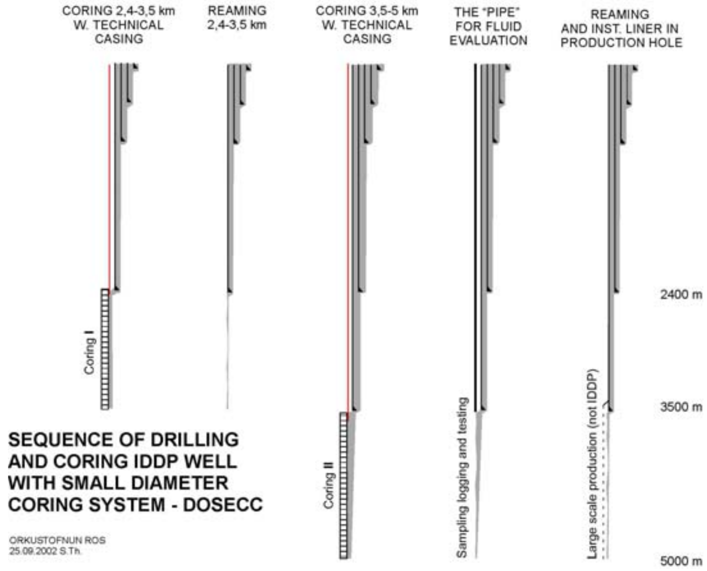

Figure 3: Sequence of drilling, coring and reaming below 2400 m. Note temporary technical casing while coring.

3 Well design

Based on the requirements set out by SAGA and information on the coring systems two well profiles were proposed (Figure4). Profile A is the larger one and can accommodate all three coring options in table 1. Well profile B is exactly the same as has already been drilled on Reykjanes, a 12-1/4" hole to 2500 m. By cementing a casing to 2400 m the well can safely be cored ahead to 3500 m or to the transition to supercritical. The idea is to use information gained from the coring the interval 2400-3500 m in deciding how deep the production casing needs to reach. The function of the production casing to isolate all fluid below the critical temperature, to allow production from the expected super-critical zone only (3500-5000 m).

The design of the wells to 2400 m is similar to a conventional high-temperature well in for case B, but case A has one size bigger casing sizes.

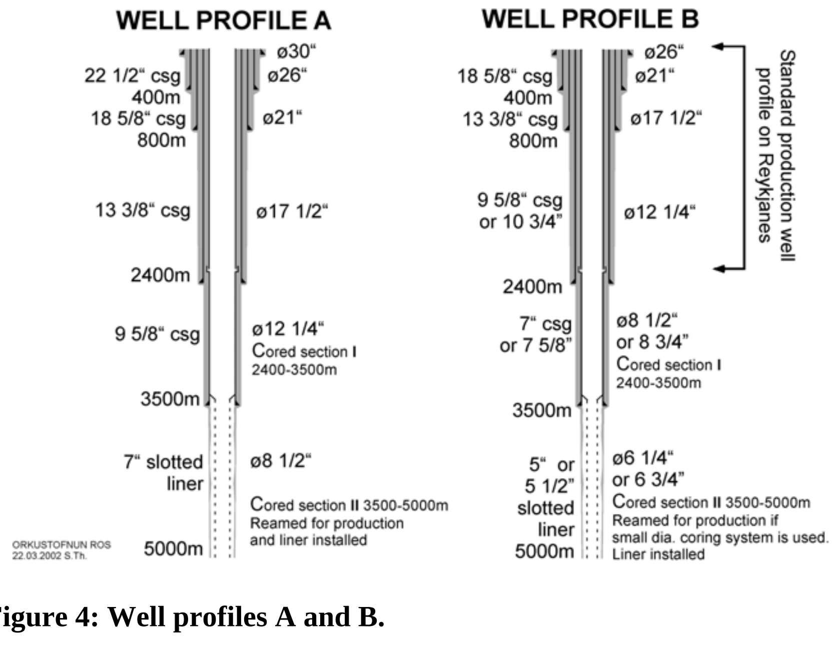

Figure 4: Well profiles A and B.

The depth of each casing string is determined, based on expected pressures in a flowing 2-phase well and being able to control any underground blow-out with heavy mud of 1.4 density (Figure5). Underground blow-out is when there is internal flow in the wellbore from a deep fractures to a zone higher up in the hole – as assumed here form the well bottom to a zone just below the casing shoe.

The well casing has to withstand extreme temperatures and pressures and the safety aspects received a special attention in the design process. Predictions of fluid circulation temperatures show that the bit can be cooled substantially while drilling a full size hole with a tri-cone bit (40 l/s), but on the other hand the coring bit receives little cooling due to its low circulation flow rate (5 l/s). Predicted flowing-well temperatures were obtained form work of the IDDP fluid evaluation group. The basis of casing design, for temperature and pressure, static and flowing, is shown in Figure 6.

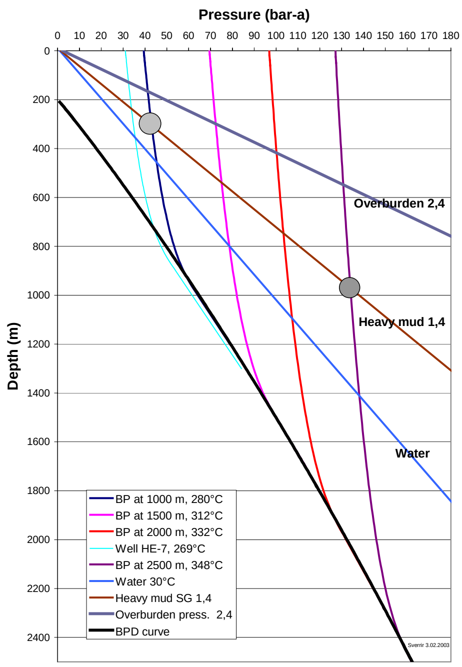

Figure 5: Pressure profiles in flowing wells used to determine minimum casing depth.

The greatest strain on the casing is due to expansion during heating and cooling of the string. Temperature changes of the casing string cause strain (tension or compression) due to hindered thermal expansion of the casing. The results for different scenarios are shown in Figure 7. The findings are that highest strain is expected when the casing string is cooled from flowing conditions to 20°C (curve 4).

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 shown in Figure 8. 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.

Internal yield pressure is in all cases higher than the wellhead shut-in pressure for the selected casing. The collapse pressure would become too great during cementing deep casings stings in one stage. Multi-stage cementing will thus have to be used.

The design of the two well types, as submitted in the Feasibility report, is shown is Figure 9.

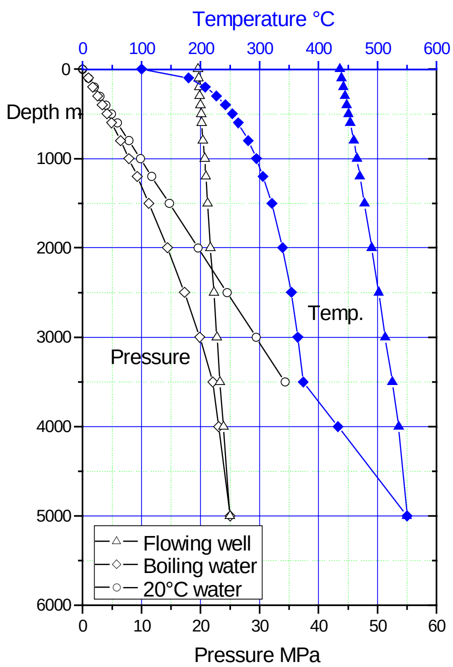

Figure 6: One scenario considered for temperature and pressure profiles in a 5000 m deep well.

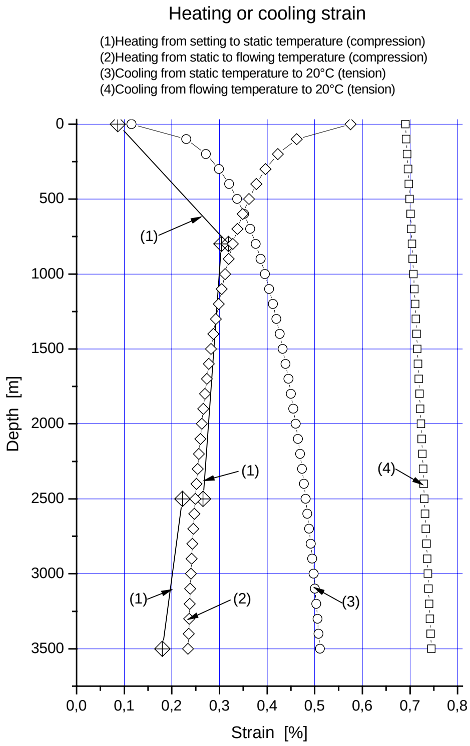

Figure 7: One-dimensional stain from hindered thermal expansion.

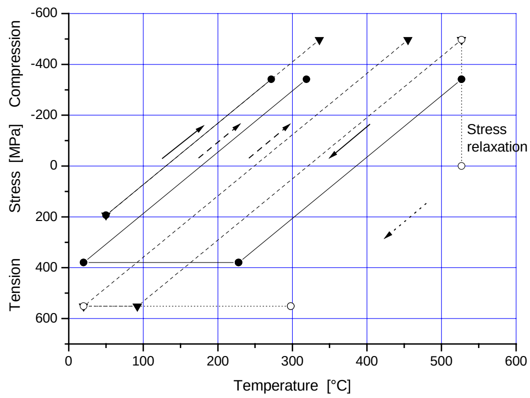

Figure 8: Axial thermal loading in casing.

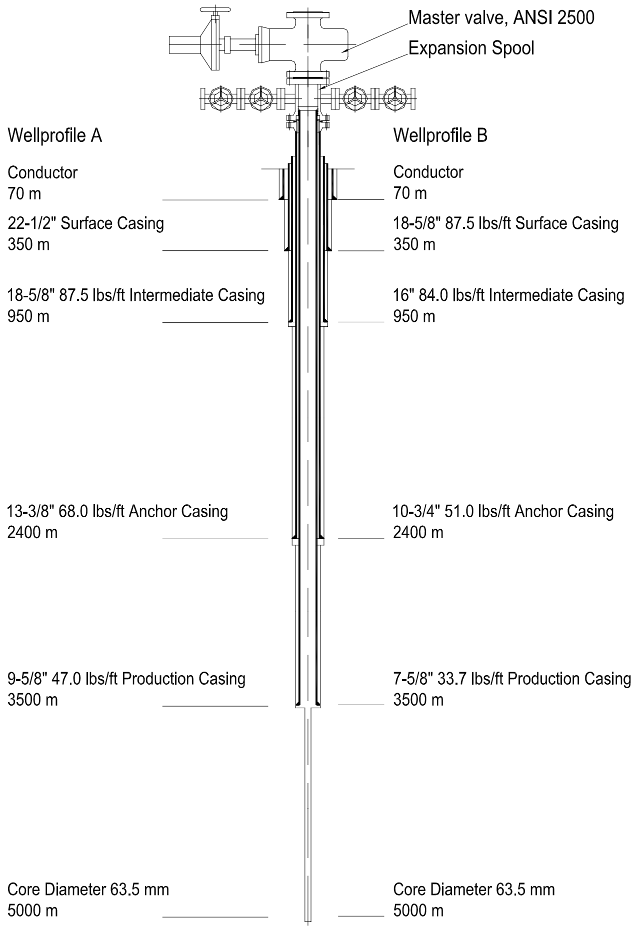

Figure 9: Casing design for the two IDDP well types. Profile A (large dia. Well) and B (small dia.).

4 Estimates

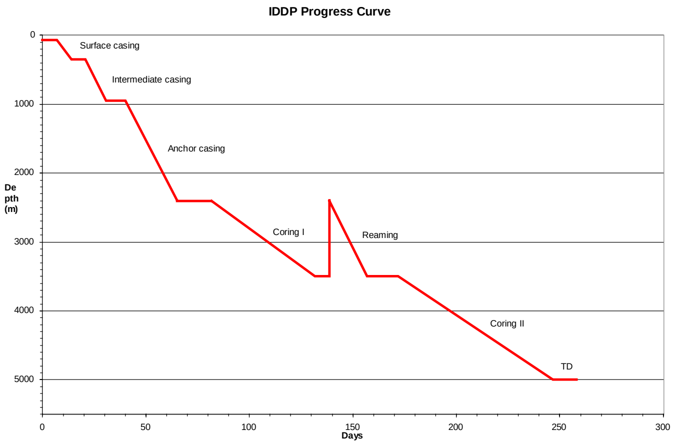

Figure 10: Time estimate for drilling well B (small dia. well).

Time- and cost estimates were made for the IDDP wells of the two selected designs. As a basis the time estimates for conventional rotary drilling considers experience gained by production drilling in Iceland. Average rate of penetration for drilling such large diameter holes is 50-60 m/day. The estimate for coring is based on a rate of penetration of 20-25 m/day depending on depth. The cost estimate is based on unit costs for rig rate, materials, logging services and personnel. The operational cost of the rig and all on-site personnel is around US$ 33,000 per day.

The time and cost estimate is broken down into three parts a) Drilling, b) Coring, c) Logging. The cost is further broken down into a) Time dependent, b) Depth dependent, c) Fixed costs, d) IDDP science. Some items are calculated separately such as casing cost, materials, logging cost etc. A contingency of 10% is applied to the total base estimate. Figure10 shows the Time vs. depth chart for a well of type B (smaller diameter hole).

The summary results of the cost estimates for wells of type A and B is shown in Table 3. Furthermore estimates were made for two "wells of opportunity", KJ-18 in Krafla and RN-12 on Reykjanes, both to be cored to 4000 m. Finally the cost of drilling well B and taking no cores was estimated. The cost and time estimates are summed up in Table 3.

Table 3: Summary: IDDP cost and time estimates. Excluding Icelandic VAT tax of 24,5%.

	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**	

5 Summary and conclusions

Deep drilling into a reservoir with supercritical conditions is a challenge both on the scientific and technical side. Such a well must be carefully designed and the equipment needed must be selected with much care to prevent accidents or well failure.

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, based on early 2002 dollars.

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.

Information on comparable drilling projects were acquired and studied. It is clear that this is a very demanding project, especially as it constitutes deep, continuous coring in what is expected to be super-critical steam conditions.

The BOP stack is robust enough to take the pressure but there are, however, temperature limitations on the BOP seals. Thus cooling ports are needed, using the side outlets on the BOP's, 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 during the coring phase (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.

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 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.

6 References

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