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DESIGN OF SLIM WELL DRILLING PROGRAMME FOR GEOTHERMAL EXPLORATION: CASE OF NGOZI, TANZANIA

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ABSTRACT

This report deals with the design of future exploration slim wells for Tanzania Geothermal Development Company (TGDC) at the Ngozi geothermal prospect in Mbeya, in the south-western part of Tanzania. The area offers a different challenge in terms of drilling infrastructure since the terrain is very mountainous and has a unique feature of a caldera that hosts Lake Ngozi. This provides challenges in terms of accessibility of the area. However, the prospect is suggested to be of high temperature, which makes it a great prospect for production of electricity.

The designing process of a geothermal well starts with the collection of comprehensive geoscientific data. These include the stratigraphy of the area, temperature gradient, boiling point depth curve and expected drilled depths. The calculation of the minimum casing setting depth, cementing quantities expected and expected wellhead pressure follows.

This paper has a proposed slim well design for a new site like Ngozi in Tanzania. The proposed design will contain a 17 ½´´ surface hole, an intermediate 12 ¼´´ hole, 8 ½´´ hole for the production casing and 6 1/8´´ hole drilled for the last section to install perforated liners. A special design for the top casing that anchors the wellhead has been particularly looked at due to its role in containing the high pressures and temperature that may build up when the well is shut off.

The paper also looks at key activities such as the selection of the rig suitable for slim well drilling, and the casing depths, casing material and cementing quantities have been discussed in detail keeping a keen eye on minimizing the costs that are involved in the drilling of the wells. Coring options for geothermal exploration have also been discussed showing further reduction in costs of exploration drilling. This is mainly due to smaller rigs used in exploration using coring technology.

1. INTRODUCTION

Slim wells can be used to confirm the size of the resource. Risk in geothermal development involves not only whether the resource exists, but also whether its size can be economically harnessed. Slim wells can play an important role in confirming the existence and the size of the resource.

Slim holes can also be used in reservoir testing. They can be used to determine the temperature and pressure variations as you move down the hole by using special pressure, temperature and spinner (PTS) logging tool(s). When utilized in the reservoir testing phase, slim holes can provide greater volumetric sampling of a prospect than production-size wells at an equivalent cost (Kaspereit and Osborn, 2017). For developing countries like Tanzania where a lot of funding comes from commercial banks where the need for a fast and assured return on investment is required, it is very important to minimize upfront cost and hence the overall cost of the project through the use of slim wells in early stages of the development of the fields. According to Mackenzie et al. (2017), the use of deep slim holes for exploration reduces the early capital spend on a project, and thus improves the success-weighted Net Present Value (NPV) of a project, particularly where there is a low probability of successfully finding a resource.

This paper looks at how a new country in the geothermal industry (like Tanzania) can approach exploration drilling with the idea of minimizing early exploration drilling costs.

2. LITERATURE REVIEW

2.1 Ngozi geothermal area

The Ngozi geothermal field belongs to Rungwe Volcanic Province (RVP), located directly south of Mbeya city southwest Tanzania at a triple junction of the East African Rift (EAR) as shown in Figure 1. The city is 822 kilometres northwest of Dar es Salaam, the country's largest commercial city.

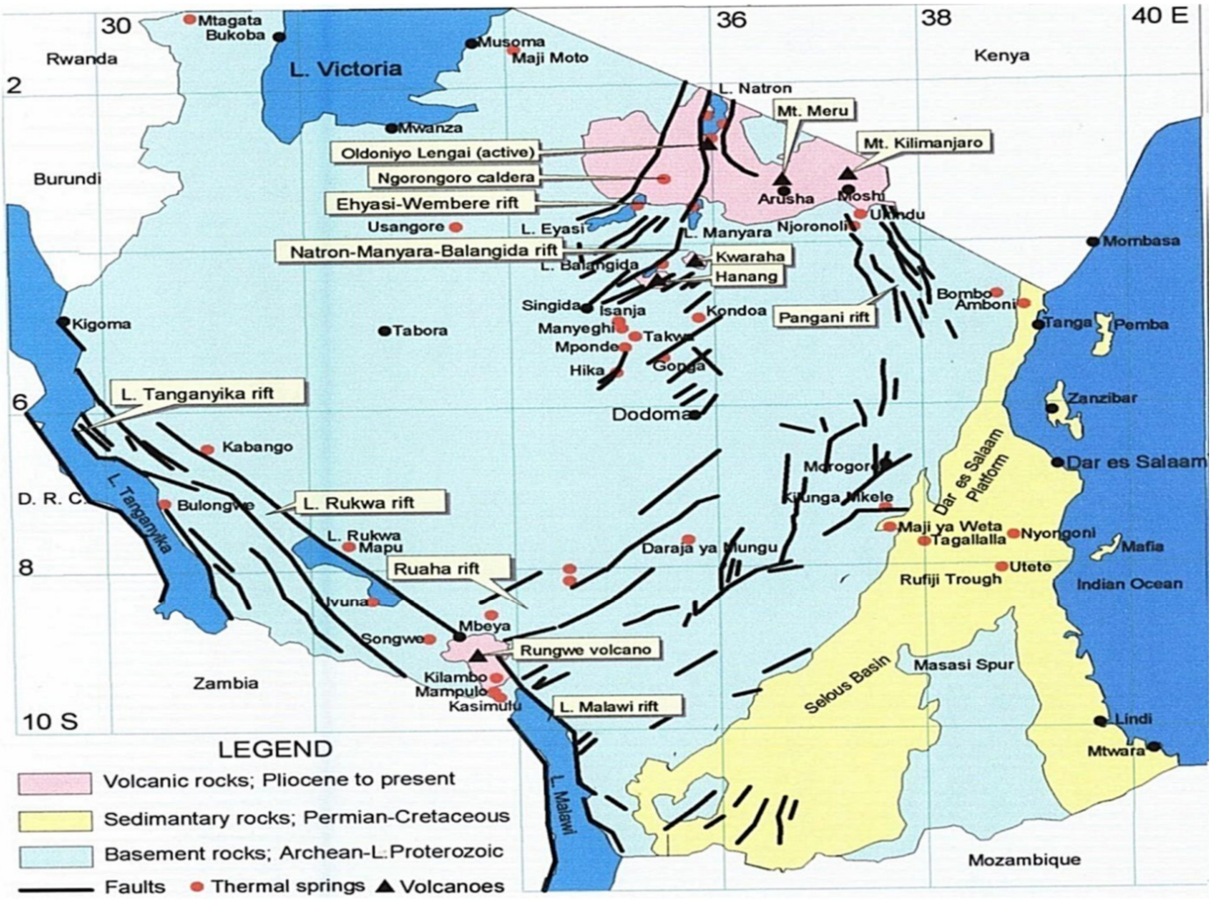


FIGURE 1: Location of Ngozi geothermal field, SW Tanzania (Ministry of Energy and Minerals, 2014)

Furthermore, the Ngozi geothermal field is located 18 kilometres from the existing Mwakibete substation with 220kV transmission (Kalimbia, 2016).

The Ngozi geothermal prospect is one of the top ranked fields in Tanzania for development of power projects and the plan is to generate up to 30 MW by 2022 in the initial phase of development and utilise heat in the brine for commercial direct-use projects.

To achieve this target, TGDC plans to undertake exploration drilling of three slim wells to confirm the existence of a viable geothermal resource and provide information on the reservoir characteristics and its potential upon the successful drilling, testing and analysing of the wells and available geo-scientific information.

2.2 Slim hole technology background

There have been many definitions of slim holes in the oil and gas industry as well as in geothermal drilling. Geothermal Risk Mitigation Facility (GRMF) for Eastern Africa provides grants for exploration drilling. The facility defines slim holes as holes drilled with less than 5” diameter of the last casing or liner.

The technology of slim well drilling has been used since the early 1920s and was studied in-depth in the 1950s. Both research and field data have shown that vertically drilled slim hole wells can be very cost effective. In the 1950s, Carter Oil Company launched an initiative to drill slim hole exploitation wells in Utah, Louisiana, Mississippi, Arkansas, Oklahoma, Illinois, and Wyoming, completing 108 wells. However, because of operational problems, such as poor drill bit and drill pipe performance, and standpipe pressures resulting from inappropriate 'mud systems, the rate of penetration decreased with sizes below 7”. As a result, the interest in slim hole drilling decreased in the sixties (Zhu and Caroll, 1995).

Slim well drilling technology has improved since then, including the combination of coring and rotary drilling of slim wells. Coring results in the collection of core samples that are very important to obtain much needed information about the reservoir and temperature versus depth in the well during the exploration stage. There have been many geothermal slim wells completed over the years in Japan, Indonesia and the Philippines.

2.3 Coring drilling in geothermal exploration

Drilling can be done in two ways; rotary drilling or coring drilling. Rotary drilling is the most common drilling technique used in geothermal drilling. It uses drilling bits to cut or crush through a rock by a rotary motion.

Coring is a technique mostly used in mining but it was also been used in geothermal drilling for some time now. It has been used to drill entire geothermal well sections in Japan, Steamboat field in Nevada, the Geysers in California, Tiwi in Philippines and Awibengkok in Indonesia (Nielson et al, 2017).

2.4 Slim well design compared to convention large well design

There are several advantages of slim wells compared to conventional large size well designs. The major advantage is the overall cost reduction in the exploration stage hence minimizing the cost of failure. Drilling slim wells instead of full-size wells in exploration is expected to reduce the cost of exploration drilling between 40-60 percent. In the report by Finger et al. (1999), states that the cost of drilling a slim well at an equivalent total vertical depth to full size well is 60 percent less than the full size well.

Other advantages include:

- Small rigs are used, hence decreasing mobilization costs. There are major differences in truckloads between different rigs used in geothermal drilling. For example, the experience in Iceland shows that for a 200 t rig, 50 truckloads are required for transport and for a 350 t rig, 100 truckloads are required to transport it and an average of 1.5 weeks to set it up. In Kenya, a 450 t rig requires around 120 truckloads and it takes two weeks to set it up ready for spudding in.

- Reduced costs of infrastructure, and hence time to prepare for slim well drilling infrastructure. These include roads, drilling pads and water supply to the drilling rig. Since this study will also look at coring drilling there is an extra advantage in water reduction during drilling when using coring instead of rotary drilling. In the report by Finger et al., 1999, they indicate that slim wells cost much less compared to full size wells due to the decreased size of the crew, drilling pads, consumables, infrastructure and less drilling fluid used. In addition, slim holes can be drilled blindly with no returns for longer intervals without reverting to blocking zones of lost circulation.

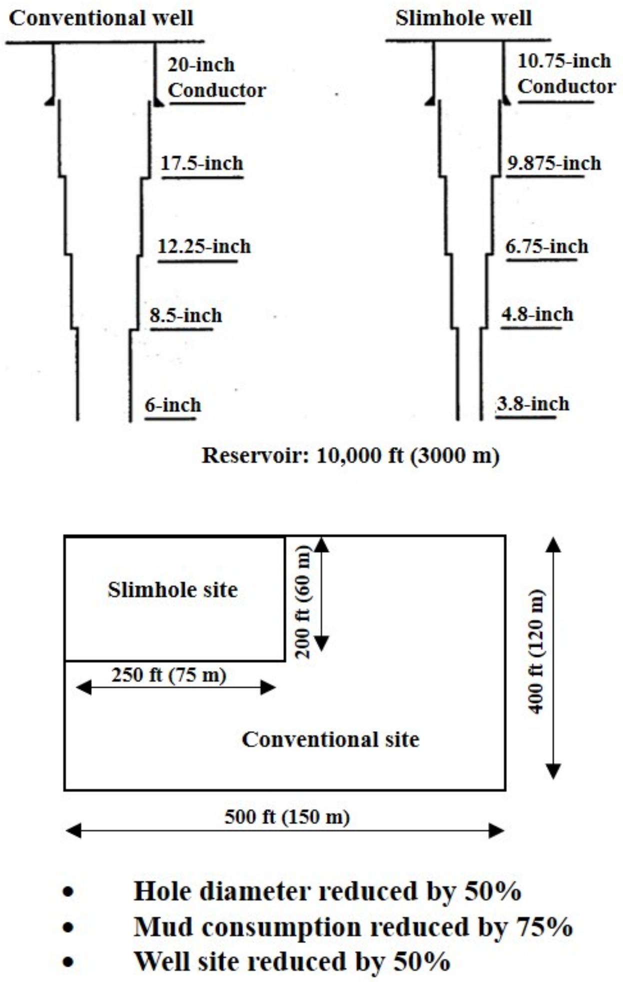


FIGURE 2: Slim well design including well pad against large size hole (Zhu and Caroll, 1995)

Figure 2 below shows in summary the major differences between slim wells and the conventional large diameter wells.

3. DESIGN OF THE SLIM WELL

3.1 Introduction

In order to get the maximum benefit of slim wells, a proper design has to be done. A slim well is not designed by just eliminating the top most design section of the full size well, that is 26” or 18 5/8” for some common designs.

For a good slim well design, it may be desirable to add an additional casing string when geological problems are encountered. The cost of adding an additional casing string can possibly reduce the overall drilling time, drilling fluid volumes and cost, if it cases off problematic or permeable formations that make it difficult to drill long intervals. Thus, an important trade-off has to be made among all the factors, paying attention to the nature of the stratigraphy of the area. For example, in regions of East Africa, collapsing formations have proved to be a big challenge in drilling. In his paper, Kahutu (2016), wrote about problems that face directional drilling in Olkaria field in Kenya, he expresses how the Olkaria

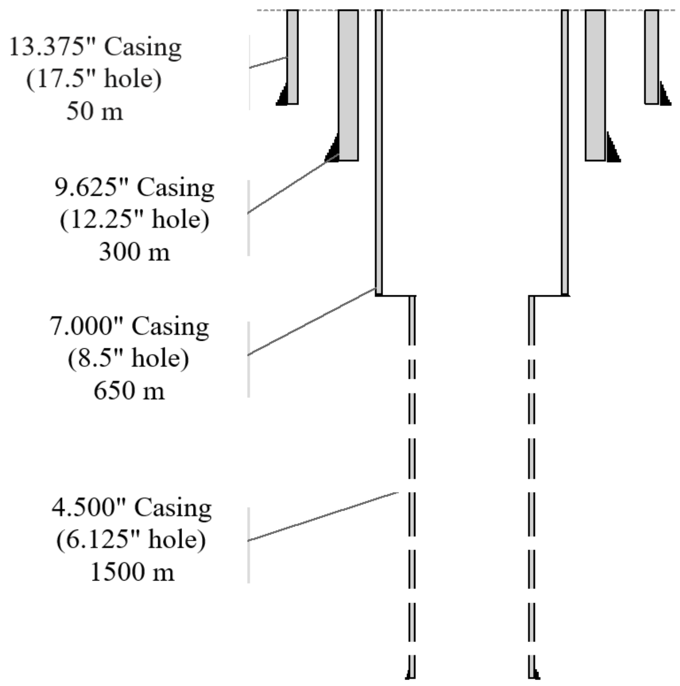


FIGURE 3: Casing design for the Ngozi slim well

geothermal field is dominated by loose and unconsolidated rocks that are prone to collapsing or sloughing when drilling using a directional bottom hole assembly.

Figure 3 shows the proposed hole and casing design for the Ngozi slim well project. The design incorporated a 9 5/8” intermediate casing section which is placed just below the water table. This casing is included due to possibly problematic upper formations, since the geology of Ngozi is not well known. For pressure containment and security of the drilling, this casing string is not required. The well will be completed with a 4-1/2” perforated liner.

3.2 Determination of minimum casing setting depth

Casing setting depths depends on both the minimum casing depths for pressure containment and safety during drilling but also the expected geological formations. Actual setting depths are then chosen based on information gathered during drilling. The on-site geologist will determine when the formations are competent enough to successfully cement the casing shoes and to determine if sufficient temperature has been reached, before setting the production casing.

The New Zealand standard (NZS 2403:2015) was used to design the casing setting depth of the slim well.

The minimum calculated casing depth for the surface casing is 50 m, for the production casing it is 650 m as shown in Figure 4.

However, due to geological reasons, an additional intermediate casing string is recommended for the exploration wells. As discussed above, in the East Africa region there are expected problems due to lost circulation and collapsing formations. This makes a design with an intermediate casing section very important to help minimize the length of each section in the upper formations. For this case, an intermediate casing is included in the design and will be set at the maximum depth of 300 m. This is decided due to the location of the water table at 200 m and the casing will thus be set just beyond the water table depending on the competency of the formation. Table 1 below shows the designed hole and casing sizes of Ngozi geothermal area.

TABLE 1: Hole sizes and casing for the Ngozi slim well

Hole (in)	**Casing (in)**	**Grade**	**Wall thickness (in)**	**Weight (lb/ft)**	**Burst (MPa)**	**Collapse (MPa)**	**Depth (m)**
17 1/2	13 5/8	K 55	0.38	54.5	18.9	7.8	0-50
12 1/4	9 5/8	K 55	0.352	36	24.3	14	50-300
8 1/2	7	K 55	0.317	23	30.1	22.5	300-650
6 1/8	4 1/2	K 55	0.29	13.5			650-1500

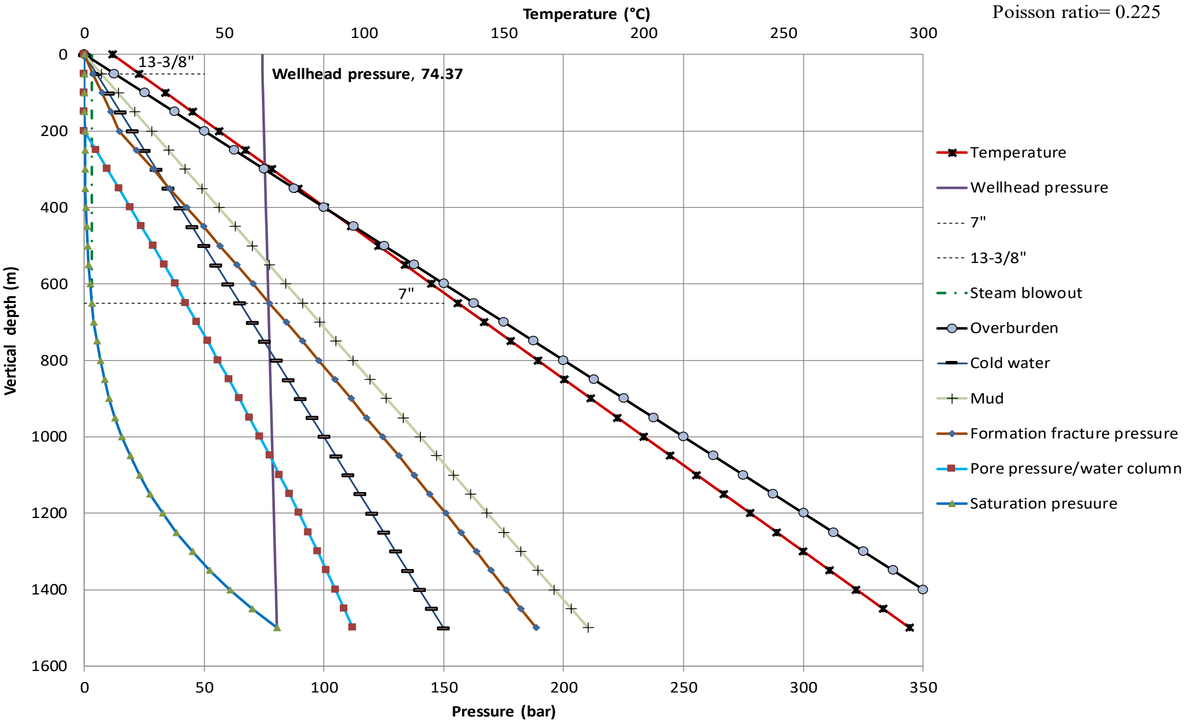


FIGURE 4: Casing setting depths for Ngozi slim well

3.3 Casing design

In order to design casings for a well, different loads have to be considered. These include the internal yield pressure, also called burst pressure, external pressure, also called collapse pressure, and the tensile loads.

3.3.1 Burst/internal yield

Casing should be designed to handle internal pressures due to pumped drilling fluid. In addition, they have to withstand pressures due to the cement column during the cementing operation. Bursting of casings is not a common phenomenon in the geothermal field. However, designs usually consider worst-case scenarios.

The maximum differential internal pressure ($\Delta P_{int.}$) in MPa will be experienced at the casing shoe when cement slurry is being pumped into the casings. This pressure can be calculated as the sum of pump pressure and slurry column minus hydrostatic pressure, as shown below:

$$\Delta P_{int.} = (L_z \rho_c - L_f \rho_f)\ xgx10^{-3} \tag{1}$$

where L_z = Total vertical length of liner or casing;
ρ_c = Cement slurry density;
L_f = Height of water column in the annulus;
ρ_f = Density of water; and
g = Acceleration due to gravity.

A design factor is applied as shown in the formula

$$\frac{internal\ yield\ pressure}{differential\ internal\ pressure} \geq 1.5 \tag{2}$$

3.3.2 Collapse/external yield

Collapse is one of the common casing failures in the geothermal drilling environment, most commonly due to trapped water between casings caused by a poor cementing job. As the well heats up after drilling, the trapped water expands even more rapidly causing the casings to collapse. Collapse can also occur due to excessive pumping pressure or static pressure from a dense liquid, for example a column of cement slurry.

In the late stages of cementing, maximum differential external pressure is experienced at the casing shoe when the annulus is filled with cement and the casing is filled with water. The external pressure design factor can be calculated by the following formula:

$$\frac{collapse\ resistance}{differential\ internal\ pressure} \geq 1.2 \tag{3}$$

Table 2 below shows the selected casing grades and their nominal weights having considered the minimum collapse resistance and minimum internal yield pressure.

Casings were selected due to their design factors for internal yield strength and external yield which were compared to the ones in Equation 2 and 3 above (African Union, 2016). The values were greater than what is required in the standard. The liners are not included in the table because they are not subjected to pressure differentials since they are perforated and not cemented. A separate calculation has been made for them.

TABLE 2: Weights and grades of casing considering burst and collapse pressures

Hole (in)	**Casing (in)**	**Differential internal pressure (MPa)**	**Differential external pressure (MPa)**	**Internal yield strength (MPa)**	**Collapse resistance (MPa)**	**Design factor for external yield**	**Design factor for internal yield**	**Check**
17 1/2	13 3/8	0.43	0.43	18.90	7.80	18.28	44.29	Ok
12 1/4	9 5/8	2.56	2.56	24.30	14.00	5.47	9.49	Ok
8 1/2	7	5.55	5.55	30.10	22.00	3.97	5.43	Ok

3.3 3 Liner selection

Since liners are perforated, they are not exposed to any pressure differentials like the casings but they are exposed to compressive stress. Liners should be hung in such a way that thermal expansion occurs at the free end and they can resist extreme buckling forces during production. There are two ways in which liners can be installed in a drilled slim well (African Union, 2016).

- Hung in tension from the liner top; and
- Supported at the shoe in compression.

The compressive stress in uncemented liners subject to self-weight and helical buckling is given by the following formula:

$$f_c = L_z \times W_p \times g \times (\frac{1}{A_p} + \frac{De}{2l_p}) \tag{4}$$

where f_c = Total extreme fibre compressive stress due to axial and bending forces (MPa);
L_z = Total vertical length of liners (m);
W_p = Nominal unit weight of liners in air (kg/m);
A_p = Cross sectional area of liners wall (mm^2);
l_p = Net moment of inertia of pipe section (mm^4);

D = Outer liner diameter (mm); and
e = Eccentricity (hole diameter- D).

Normally liners are bent slightly due to compressive stresses. They also take a slight bend limited by the walls of the hole. The design factor checks to avoid excessive liner bending and buckling as shown below

$$\text{design factor } = \frac{minimum\ yield\ stress\ \times\ R_j}{total\ compressive\ stress} \geq 1 \tag{5}$$

Table 3 below represents the calculation using formulas 4 and 5 above to check whether the selected liner, which is K 55, 4 ½ inch, 13.5 lb/ft satisfies the design factor criterion, which it does.

TABLE 3: Compressive stress calculation for liners

Casing outer diameter (mm)	**Eccentricity (mm)**	**Weight of liners (kg/m)**	**Cross sectional area (mm^2)**	**Moment of inertia of the liner (mm^4)**	**Compressive force (MPa)**	**Design factor**
114.30	57.15	17.88	2,469.55	3,547,610.35	197.62	1.34

3.3.4 Calculation for containment pressure in production casing

Normally, the anchor casing has to withstand wellhead pressure because the wellhead will be placed on it. For this case there are three casings: the surface casing, intermediate casing and production casing. The wellhead will be placed on the production casing, making it effectively the anchor casing as well. As for subsequent wells it is unclear whether the intermediate casing is used and additionally if it is used it is unclear if the depth of the intermediate casing is sufficient to make it the anchor casing. According to the New Zealand 2015 standard, the first 25 m of the anchor casing have to be designed according to ASME.

Thus, the wellhead will be placed on the 7” casing. The calculation below will determine if the maximum allowable pressure according to ASME (2012) is sufficient to contain the well head pressure.

Calculation of maximum allowable pressure

$$P = \frac{2SE(t_m - A)}{D_o - 2y(t_m - A)} \tag{6}$$

where P = Maximum internal design pressure;
y = A coefficient obtained from ASME (2012). The value is always 0.4 for casings;
t_m = Wall thickness (mm) given by multiplying API thickness by 0.875 = 0.875 × 8.1 = 7.088 mm
D_o = Outside diameter of pipe (mm)= 177.8 mm (production casing)
A = Additional thickness (mm), corrosion/erosion allowance (0-3 mm) = 1.5 mm (average); and
SE = Maximum allowable stress in material due to internal pressure and joint efficiency at the design temperature.

But,

$$SE = \frac{1.1S_tR_t}{3.5} \tag{7}$$

$$SE = \frac{1.1S_yR_y}{3} \tag{8}$$

where S_t = Specified minimum tensile strength at room temperature, MPa= 655 MPa;
S_y = Specified minimum yield strength at room temperature, MPa= 379 MPa;
R_t = De-rating factor of the tensile strength at elevated temperatures= 0.86 (at temperature of 300°C); and
R_y = De-rating factor of the yield strength at elevated temperatures= 0.8 (for K 55 material at temperature of 300°C).;

$$SE = \frac{1.1 \times 655 \times 0.86}{3.5} = 177.04\,MPa \tag{9}$$

$$SE = \frac{2 \times 379 \times 0.8}{3} = 202.13\,MPa \tag{10}$$

Since the maximum allowable stress is the lower of the two according to the ASME (2012) code, then 177.04 MPa is selected.

From Equation 4 above,

$$P = \frac{2 \times 177.7 \times (7.088 - 1.5)}{177.8 - 2 \times 0.4 \times (7.088 - 1.5)} \tag{11}$$

Therefore, maximum internal design pressure: $P = 11.46\ MPa$

Allowance for variation from normal operation

The maximum internal pressure and temperature allowed shall include considerations for occasional loads and transients of pressure and temperature (ASME, 2012). There are always situations where pressures and temperatures occur in the well. Piping systems should be designed to occasionally cater for these higher than designed temperatures and pressures.

According to the ASME (2012) code, these variations are allowed at:

- 15% if the event occurs for not more than 8 hours at any time and not more than 800 hours per year or;
- 20% if the variations occur no more than 1 hr and not more than 80 hours per year.

Therefore, looking at the calculated maximum internal pressure and incorporating the 15% variation,

$$\begin{aligned} &Allowance\ for\ variation \\ &= 0.15 \times maximum\ internal\ pressure \\ &+ maximum\ internal\ pressure \end{aligned} \tag{12}$$

$$Allowance\ for\ variation = 0.15 \times 11.46 + 11.46 \tag{13}$$

$$Allowance\ for\ variation = 13.18\ MPa \tag{14}$$

Since the maximum internal design pressure (13.18 MPa) is greater than the maximum expected wellhead pressure (7.473 MPa), the casing design is appropriate for the well.

3.4 Tensile loading calculations for the casings

It is important to check if the casing can withstand its own weight when being lowered into the well. This is done by looking at the tensile loading of the casing. Tensile loading will be analysed for the anchor and production casing as the surface casing is very shallow and will be considered in analysing compressive and buckling forces.

3.4.1 Casing running

In the first case an axial load is calculated when running casings as shown in Table 4 below.

TABLE 4: Tensile load when running casings

			Casing running		
Casing (in)	**Weight (lb/ft)**	**Length (m)**	**Weight of casing (kN)**	**Tensile load (kN)**	**Safety factor**
9 5/8	36.00	300.00	157.67	338.03	7.43
7	23.00	650.00	218.25	392.56	4.15

3.4.2 When cementing

According to the African Union (2016), tensile force at any depth is the sum of weight in air of the casing and the weight of the casing content minus the buoyance effect of any fluid displaced by the casing.

$$F_{hookhand} = F_{csg\ air\ wt} + F_{csg\ content} - F_{displaced\ fluids} \tag{15}$$

$$F_{csg\ air\ wt} = L_z \times W_p \times g \times 10^{-3} \tag{16}$$

$$F_{csg\ contents} = \sum \rho_{if} L_{if} \frac{\pi D^2}{4} \text{x}\ g\ \text{x}10^6 \tag{17}$$

$$F_{displaced\ fluids} = \sum \rho_{ef} L_{ef} \frac{\pi D^2}{4} x\ g\ x10^6 \tag{18}$$

where $F_{hookhand}$ = Surface force suspending casing that is subject to gravitational and static hydraulic loads (kN);

$F_{csg\ air\ wt}$ = Weight of casing in air (kN);

$F_{csg\ content}$ = Weight of internal contents of casing (kN);

$F_{displaced\ fluids}$ = Weight of fluids displaced by casing (kN);

L_z = Total vertical length of liner or casing (m);

W_p = Nominal unit weight of casing in air (kg/m);

L_{if} = Vertical length of a section of fluid having the same density within the casing (m);

ρ_{if} = Density of section of fluids with constant density within the casing (kg/l);

L_{ef} = Vertical length of a section of fluid having the same density within the external annulus (m); and

ρ_{ef} = Density of section of fluids with constant density within the annulus (kg/l).

The design factor that is used to check for tensile loading is given by

$$\text{Design factor } = \frac{maximum\ tensile\ strength}{maximum\ tensile\ load} \tag{19}$$

The design factor must be greater than 1.8 for the casing to be able to sustain its own weight under tensile loading (African Union, 2016). In the formula above, the maximum tensile load is equivalent to the hook load and the maximum tensile strength can be obtained from a drilling data book.

Assuming the density of cement is 1.87 kg/l for design purposes, Table 5 below shows the compliance with the design factor for tensile loading on different casing sections.

TABLE 5: Checking for tensile strength of the selected casings

			When cementing						
Casing (in)	**Weight (lb/ft)**	**Length (m)**	**Cross-sectional area (mm^2)**	**Buoyancy force (kN)**	**Weight of casing (kN)**	**Weight of cement (kN)**	**Total axial load (kN)**	**Design factor**	
9 5/8	36.00	300.00	6,623.02	138.18	157.67	221.94	241.43	10.40	OK
7	23.00	650.00	4,292.95	158.32	218.25	244.87	304.80	5.35	OK

3.5 Cementing of a slim well

Cementing is a very important process in geothermal drilling because it helps to keep away all the unwanted zones separating the casing from the wellbore. Proper cementing will ensure an effective production process without failures in the well due to, for example, trapped water in the casings.

There are several methods for cementing of wells in a geothermal environment. These include cementing through the casings, the inner string method and reverse circulation method. All these methods have their strengths in some scenarios and weaknesses in others. Cementing in this case will be done using the inner string method. The method is performed by pumping cement slurry through the casing inside a drill pipe. This is due to the following advantages of the inner string cementing method:

- Variable amount of cement slurry rather than a pre-fixed amount. Comparatively with through the casing (with plugs) method, a full amount of cement slurry is required to be pumped even if returns appear at the surface (which means that you can pump more than required). Additionally, it means that you may stop pumping even if the cement has not reached the surface;
- Less time needed to pump cement slurry because you do not have to fill the inside of the entire casing before it reaches the annulus.

3.5.1 Calculation of cement slurry quantity

The casing program of the designed slim well will have the following sections:

Diameter of conductor casing (1 m): 20” = 0.508 m
Diameter of surface hole (0-50 m): 17 1/2” = 0.4445 m
Diameter of surface casing (0-50 m): 13 3/8”= 0.339725 m
Diameter of intermediate hole (50-300 m): 12 ¼”= 0.31115 m
Diameter of intermediate casing (50-300 m): 9 5/8”= 0.244475 m
Diameter of production hole (300-650 m): 8 ½” = 0.2159 m
Diameter of production casing (300-650 m): 7” = 0.1778 m

Assumptions:

- Float collar is placed 1 joint above the bottom and each casing pipe is 9 m;
- Excess of 60% of the designed cement slurry;
- Each casing is 9 m long; and
- Rat hole 1 m.

Cement slurry content needed for each section is calculated and the results are shown in Table 6 below:

TABLE 6: Cementing slurry quantities for each hole section

	Volume of cement in each section (m^3)		
	Surface casing cementing	**Intermediate casing cementing**	**Production casing cementing**
Cementing between casings	0.09	1.68	4.65
Cementing between annulus and open hole	4.96	11.59	6.58
Cementing in rat hole	0.25	0.12	0.06
Cementing inside casing	0.73	0.73	0.37
Total for section	6.02	14.12	11.66

Therefore, total slurry expected to be used in this well will be 31.80 m^3.

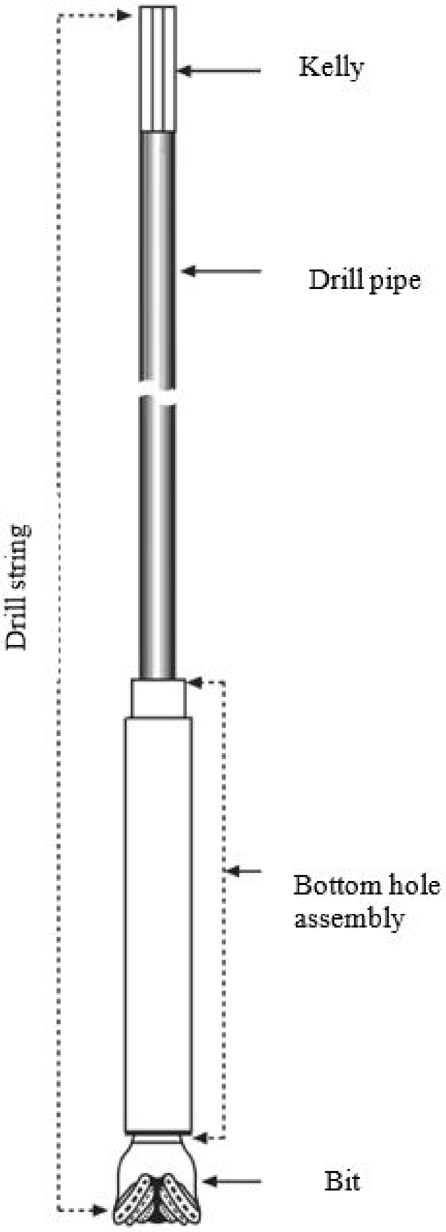


FIGURE 5: Drill string (Heriot-Watt University, 2010)

3.6 Drilling rigs used in slim hole drilling

As shown in the literature review, slim hole drilling is an old technology, especially in oil and gas drilling. However, in geothermal drilling the technology has not been widely adapted. For example, despite more than 200 wells drilled in Kenya, there are no records of slim wells drilled in this area either early during the exploration stage or in reservoir size confirmation stage. Apart from other reasons for its relatively low acceptance in geothermal environment, the depth limitation was one of the major hindering factors. However according to Thórhallsson and Gunnsteinsson (2012), a rig manufacturer in Sweden, recently developed a coring rig for deep geothermal exploration to 2500 m.

Drilling of slim wells can be done through rotary drilling only, coring drilling only (most common in mining operations) or a combination of rotary and coring drilling sometimes referred to as hybrid drilling.

The geothermal industry needs multipurpose slim hole rigs (with both coring of production section and rotary or hammer drilling of the top section) with a minimum drilling capacity of 31,750 kg (Nielson et al., 2017). This means that the minimum weight of a rig to be used in slim well drilling is 32 tonnes. In order to calculate the maximum hook load both the weight due to the drill string and casings are considered.

3.6.1 Weight of the drill string

Some drilling rigs are classified according to the weight they can handle, technically called the hook load. Apart from weight of the casings, the drilling string can give a significant load to the drilling rig.

Geothermal drill string is made up of the bottom hole assembly (BHA) and the drill pipes as shown in Figure 5. A large part of the drilling string is made up of drill pipes. According to

Heriot-Watt University (2010), 90%-95% of the drill string is drill pipes

Since the area is a virgin field, that is no wells have been drilled, then the torque value can hardly be estimated. However, it is a rule of thumb that drill collars will have larger diameters than drill pipes since drill collars are supposed to provide the weight on the bit. Thus, considering the final diameter of the well, and the necessary weight on bit (WOB) that will ensure that the drill string is heavy enough to complete the well, the selected drill string is 1350 m of 3 ½” drill pipes (13.3 lb/ft **NC38 IF** threads **EU,** grade **E,** premium class) and 150 m of 4” drill collars (1 ¼” ID) for weight on bit to drill down to 1500 m depth.

From the preliminary data that is available, the weight of the drill string can be calculated as summarized in Table 7, where:

Buoyancy factor for water = 0.873;
Water table = 200 m;
Weight of drill pipes = 20.76 kg/m; and
Weight of drill collars = 57.43 kg/m.

TABLE 7: Drill string weight

	Length in air (m)	**Length in water (m)**	**Weight air (kg)**	**Weight in water (kg)**	**Total (kg)**	**Total weight of liners and drill pipes (kg)**
Drill pipes	200	1,150	4,152	20,842	24,994	
Drill collars	-	150	-	7,520	7,520	32,514

3.6.2 Weight of the casings

Table 8 below shows the calculation of weights of different casings that are expected to be used to case off different formations after the drilling of a given section, where:

Weight of surface casings = 79.5 daN/m;
Weight of production casings = 67.1 daN/m;
Weight of liners = 19.7 daN/m; and
Weight of 3 ½´´ drill pipes = 20.76 kg/m.

TABLE 8: Casing weights

	Length air (m)	**Length in water (m)**	**Weight air (kg)**	**Weight in water (kg)**	**Total weight (kg)**	**Total weight of liners and drill pipes (kg)**
Surface casing (13.375")	50	0	4,053	0	4,053	
Intermediate casing (9 5/8")	200	100	10,707	4,674	15,380	
Production casing (7")	200	450	6,852	13,460	20,312	
Drill pipes (3 1/2")	200	450	4,152	8,156	12,308	
Liners (4 1/2")	0	850	0	14,906	14,906	27,214

From Tables 7 and 8 the heaviest hook load is 32,514 kg from the drill string, that is approximately 33 tonnes.

From Heriot-Watt University (2010), the yield strength of 3 ½" 13.3 lb/ft **NC38 IF** threads **EU,** grade **E,** premium class, is 94300 daN.

But

$$allowable\ tensile\ strength = 0.9\ \times\ tensile\ yield\ strength \tag{20}$$

$$allowable\ tensile\ strength = 0.9\ \times\ 94300 \tag{21}$$

$$allowable\ tensile\ strength = 84870\ daN = 86.54\ tonnes \tag{22}$$

Now the safety factor for the drill pipes has to be checked. The safety factor is calculated as:

$$safety\ factor = \frac{\text{allowable tensile strength}}{\text{maximum hook load}} \tag{23}$$

$$safety\ factor = \frac{86.54}{38} \tag{24}$$

$$safety\ factor = 2.27 \tag{25}$$

This safety factor for the drill pipes is above the acceptable limits of the minimum value which is considered 1.33 (Sigurdsson, 2018b).

Apart from the allowable tensile strength of the drill pipes, the margin of over pull has to be considered. The margin of over pull is the extra tension which can be safely applied on the drill string when it is stuck without breaking it. An over pull of 20 tonnes should be sufficient for drilling a slim well down to 1500 m (Sigurdsson, 2018b).

Also, the minimum capacity of the drilling rig is given as

$$\begin{aligned} &minimum\ capacity\ of\ drilling\ rig \\ &\quad = (maximum\ hook\ load + margin\ of\ overpull) \\ &\quad \times design\ factor \end{aligned} \tag{26}$$

The design factor for a drilling rig that goes to 1500 m is approximately 1.15 (Sigurdsson, 2018b).

Thus,

$$minimum\ capacity\ of\ drilling\ rig = (33 + 20) \times 1.15 \tag{27}$$

$$minimum\ capacity\ of\ drilling\ rig = 60.95\ tonnes \tag{28}$$

Thus, a minimum rig capacity to be used by TGDC to drill 1500 m slim wells based on the proposed design will be a 61 tonne rig.

3.7 BOP equipment selection for slim hole wells

3.7.1 Selection of Blowout Preventer

The high pressures and temperature characteristics of geothermal fields require proper Blowout Preventer Equipment (BOPE) to be to be installed when drilling geothermal wells. Due to the reduced diameters of slim wells, high pressures should be expected, and thus countermeasures have to be taken.

BOPs can be defined as high pressure valves used during drilling to shut off (seal) the well. They are used to prevent the uncontrolled flow of fluid out of the well. The BOP stalk usually contains:

- Blind ram or shear ram for completely sealing off the well;

- Pipe ram for closing around drill pipes; and
- Annular BOP for closing around any object.

The BOP should contain a 3" kill line and choke line to bleed off the gas (Sigurdsson, 2018a). In addition, there is a rotating head installed at the top that diverts the direction of the hot geothermal fluid to protect the crew and mast. The crew should be protected for safety reasons while the mast should be protected from geothermal fluids that come out of the well because they can be very corrosive.

In this design a 13 5/8” annular BOP will be used to drill the 12 1/4 " (intermediate casing) section from 50 m to 300 m. It will be placed on the 13 3/8" casing. Another BOP stack of 11” will be used to drill the 8 ½ " (production casing) section from 300 m to 650 m. It will be placed on the 9 5/8" casing. The same BOP will be used to drill the 6 1/8” (production section) from 650 m to 1500 m. Master valve may be added before drilling this section.

Since the expected wellhead pressure is 7.4 MPa or 1088 psi (from Figure 4 above), then a BOP with working pressure greater than that will be suitable for the well. The limiting factors will be cost of the BOPs and the available standards in the market. Hydrill type BOP is used for this case. Table 9 below represents the type of BOP selected.

TABLE 9: Selected BOP size

	Hydrill.	Size (inch)	Pressure (psi)	Weight (kg)
Intermediate section	Annular	13 5/8	3000	5845
Production section to 1500 m	Ram	11	3000	2540
	Annular	11	3000	3744

3.7.2 Selection of wellhead

From Figure 4 above, the wellhead, the pressure is 74.73 bar, which is equivalent to the saturated pressure of 290°C. As shown in Figure 6, the wellhead temperature, represented by a green line in the Figure, crosses the saturated steam line between the ANSI 600 and ANSI 400 lines.

Thus, an ANSI 600 wellhead is selected. A 6” casing head flange and a 6” master valve, both ANSI 600, are placed on top of the 7” production casing.

The wellhead components include (Hole, 2008):

- Casing Head Flange (CHF) that is normally installed on top of the anchor casing (in this case it will be the production casing);
- Double flanged expansion (adaptor) spool. This provides room for the anchor casing to expand to a tolerable extent due to thermal expansion as the well heats up. For this design, the adaptor will not be used since the production casing is used as the anchor casing; and
- Master valve.

4. SLIM HOLE TESTING

4.1 Introduction to well testing

After drilling, slim wells undergo testing. Normally, a well is flown in order to undergo proper testing. Tests are carried out to determine the productivity, injectivity, drawdown and storativity of the well.

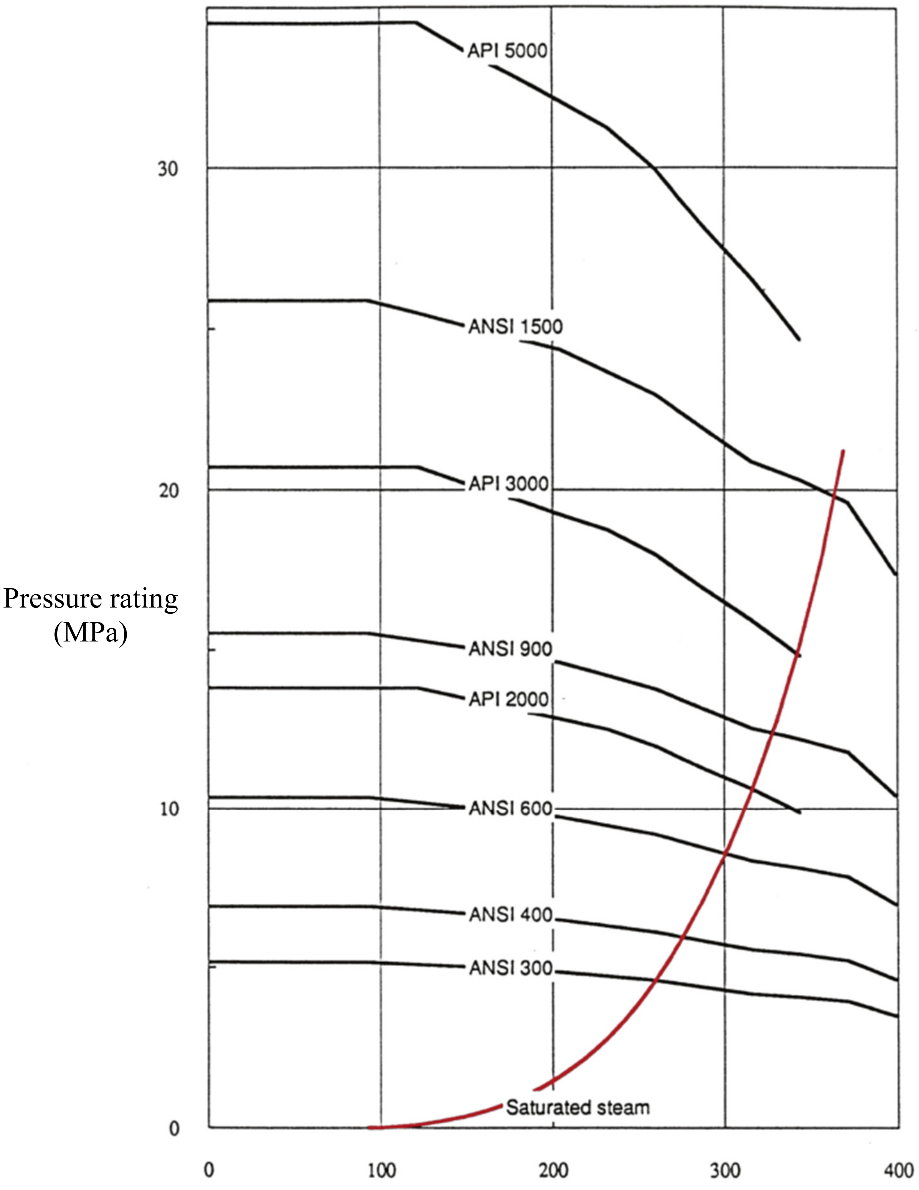
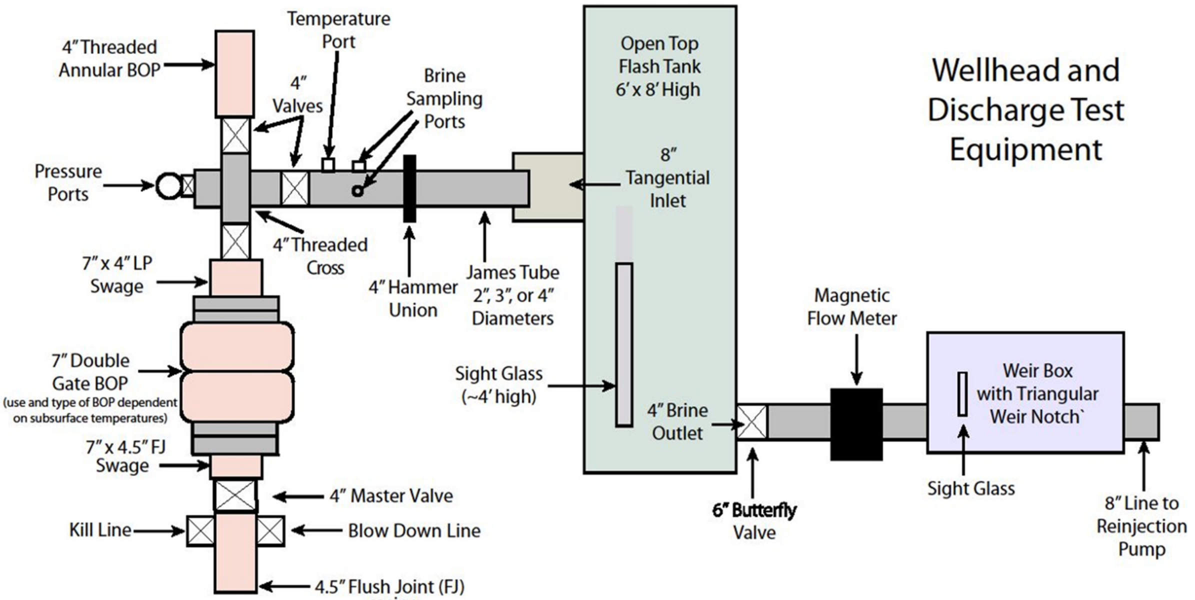


FIGURE 6*:* Wellhead working pressures (African Union, 2016)

Well testing is used to determine key reservoir parameters, such as permeability and storativity along with reservoir boundary conditions, if a test is sufficiently long lasting (Axelsson, 2013). Such estimates ultimately give key information for the conceptual model development.

There are two kinds of wells: those with artesian flow, normally high temperature and pressure wells or non-artesian wells that have to be air lifted. Moreover, some wells may require stimulation and then they flow by themselves afterwards, some may require constant stimulation throughout the process. The latter may be caused by many factors but normally it is not a good indication for the conditions of the reservoir, probably it is too cold or a cold flow intersects the pay zone. Either way, careful testing and analysis will be required.

Figure 7 shows an arrangement of apparatus during testing of slim wells.



Modified after Goranson, 1996

FIGURE 7: Equipment layout for flow testing slim well (Nielson et al., 2017)

4.2 Slim well testing in relation to large diameter hole

Slim well testing methodologies are similar to those conducted on large-diameter wells; although produced and/or injected fluid volumes are much less. Pressure, temperature and spinner (PTS) logs in slim holes under static conditions can be used to characterize temperature and pressure distribution in the geothermal reservoir. In many cases, it is possible to discharge slim holes and obtain fluid samples to delineate the geochemical properties of the reservoir fluid (Nielson et al., 2017).

Also, in the latter case, drawdown and build up data obtained using a downhole pressure tool can be employed to determine formation transmissivity and well properties. If it is not possible to discharge a slim hole, an injection test can be performed to obtain formation transmissivity. Given the discharge (or injection) data from a slim hole, discharge properties of a large-diameter well can be inferred using wellbore modelling (Nielson et al., 2017).

Finally, slim hole data (pressure, temperature, transmissivity, fluid properties) together with reservoir simulation can help predict the ability of the geothermal reservoir to sustain power production. To compute the probable discharge characteristics of a large-diameter well, a relationship between injectivity and/or productivity of slim holes and large-diameter production and/or injection wells is required (Nielson et al., 2017).

5. FURTHER STUDIES

5.1 Further areas for studies

There are several advantages of coring drilling in geothermal exploration, the most important being cost reduction in exploration stage. This is a key factor since the bankability of a geothermal project in the early exploration stage is a huge challenge. According to Nielson and Gary (2016), drilling a slim well using coring drilling reduces the cost of drilling by 25% to 35% of the cost of a large size hole drilled to a similar depth. Also according to Finger and Blankenship (2010), slim well coring provides cost saving compared to rotary drilling due to two major advantages: smaller casings, tools (for example reamers, and bits), and cementing volumes, and drilling can still take place with complete loss of circulation.

Apart from reduction in drilling and equipment costs, coring provides an opportunity to collect core samples that give a full picture of the stratigraphy. Coring design in geothermal wells usually include coring in the production section because it enables the collection of very important information about the reservoir.

Coring can offer further minimization of the final diameter of the well, which may mean a reduction in drilling costs. Coring can be designed using PQ, HQ and NQ coring whose final drilling diameters are less (or equal for the case of PQ coring) than the 4.5”. However, this study has discussed the coring of slim wells in regard to collection of necessary reservoir information so that the results can be used to drill larger production wells. The structural integrity and the minimum diameter for slim wells to produce remains a subject of interest. Three design cases have been looked at as follows.

5.1.1 The minimum exploration design with a hybrid rig

The design represents the minimum design of a slim well using coring drilling with the smallest coring rod that is a NQ rod as shown in Table 10 below.

TABLE 10: First alternative design ending with NQ coring

	Hole (in)	**Casing (in)**	**Casing depth (m)**
Design 1 (Minimum exploration)	8 1/2	7	0-80
	6	4 1/2	0-350
	HQ Coring (3.77)	3.77	0-650
	NQ Coring	open hole	650-1500

Table 11 below shows the calculation of the weight of the hook load expected to be carried by the drilling rig with this design.

TABLE 11: Calculation of hook load weight for the first alternative design

	Length air (m)	**Length in water (m)**	**Weight air (kg)**	**Weight in water (kg)**	**Total weight (kg)**
Surface casing (7")	80	0	2,741	0	2,741
Intermediate casing (4 1/2")	200	150	4,018	2,631	6,648
HQ casing (3.77")	200	450	2,300	4,518	6,818

From Table 11 the heaviest hook load is 6,818 kg from the drill string, that is equivalent to 6.818 tonnes.

The design factor and over pull assumed for a hybrid rig that goes to 1500 m is approximately 1.1 and 10 tonnes respectively (Sigurdsson, 2018b).

Thus,

$$minimum\ capacity\ of\ drilling\ rig = (6.818 + 10) \times 1.1 \tag{29}$$

$$minimum\ capacity\ of\ drilling\ rig = 18.50\ tonnes \tag{30}$$

Thus, a minimum rig capacity to be used by TGDC to drill 1500 m slim wells based on the proposed design will be a 19 tonne rig.

5.1.2 The intermediate exploration design with a hybrid rig

The design represents the intermediate design between the three proposed alternative designs of a slim well using coring drilling with a HQ coring rod as shown in Table 12 below.

TABLE 12: Second alternative design ending with HQ coring

	Hole (in)	Casing (in)	Casing depth (m)
Design 2 (intermediate exploration)	8 1/2	7	0-80
	6 1/8	5 1/2	0-350
	PQ Coring	4 1/2	0-650
	HQ Coring (3.77)	open hole	650-1500

From Table 13 above, the heaviest hook load is 11,909 kg from the drill string, which is equivalent to 11.909 tonnes

TABLE 13: Calculation of hook load weight for the second alternative design

	Length air (m)	Length in water (m)	Weight air (kg)	Weight in water (kg)	Total weight (kg)
Surface casing (7")	80	0	2,741	0	2,741
Intermediate casing (5 ½")	200	150	4,160	2,724	6,884
Production casing (4 ½")	200	450	4,018	7,892	11,909

The design factor and over pull assumed for a hybrid rig that goes to 1500 m is approximately 1.1 and 10 tonnes respectively (Sigurdsson, 2018b).

Thus,

$$minimum\ capacity\ of\ drilling\ rig = (11.909 + 10) \times 1.1 \tag{31}$$

$$minimum\ capacity\ of\ drilling\ rig = 24.1\ tonnes \tag{32}$$

Thus, a minimum rig capacity to be used by TGDC to drill 1500 m slim wells based on the proposed design will be a 25 tonne rig.

5.1.3 The maximum production design with a hybrid rig

The design represents the maximum hybrid design that can be used to produce from a slim well. The alternative design uses coring drilling with a PQ coring rod as shown in Table 14 below.

TABLE 14: Third alternative design ending with PQ coring

	Hole (in)	Casing (in)	Casing depth (m)
Design 3 (Maximum production)	12 1/4	9 5/8	0-50
	8 1/2	7	0-300
	6 1/8	5 1/2	0-650
	PQ Coring (4.8)	open hole	650-1500

TABLE 15: Calculation of hook load weight for the third alternative design

	Length air (m)	**Length in water (m)**	**Weight air (kg)**	**Weight in water (kg)**	**Total weight (kg)**
Surface casing (9 ⅝")	50	0	481	0	481
Intermediate casing (7")	200	100	6,852	2,991	9,843
Production casing (5 ½")	200	450	4,160	8,172	12,332

From Table 15 above, the heaviest hook load is 12,332 kg from the drill string, which is equivalent to 12.332 tonnes.

The design factor and over pull assumed for a hybrid rig that goes to 1500 m is approximately 1.1 and 10 tonnes respectively (Sigurdsson, 2018b).

Thus,

$$minimum\ capacity\ of\ drilling\ rig = (12.332 + 10) \times 1.1 \tag{33}$$

$$minimum\ capacity\ of\ drilling\ rig = 24.57\ tonnes \tag{34}$$

Thus, a minimum rig capacity to be used by TGDC to drill 1500 m slim wells based on the proposed design will be 25 tonnes rig.

According to Thórhallsson and Gunnsteinsson (2012) coring rigs have been limited in depth to between 1000 m and 1500 m. There are also questions as to whether it is possible to induce flow in such small diameters and produce from the wells in high temperature geothermal fields. However, a company in Sweden has recently designed a coring rig for geothermal drilling exploration to 2500 m.

The author thinks that more research has to be done on slim well design using a combination of rotary and coring due to the crucial advantages of slim well coring as discussed above. More cost cutting may be realized when using coring in geothermal exploration drilling.

6. CONCLUSION

Proper designing of wells in a geothermal environment is very important especially for new sites like Ngozi in Tanzania where there is limited information about the lithology of the site. The casing design should consider some worst-case scenarios for the first wells. The design will improve as more information is gathered. For example, it is suspected that there will be collapsing formations which is why the design for the first slim well will start with a 13 3/8’’ casing. This design can change in the subsequent wells to the next smaller diameter if the formation proves to be stable enough. This will reduce drilling costs.

In selecting a contractor to help the company in drilling slim wells, the owner has to get a contractor that has done slim wells before in geothermal environment. The experience that the contractor has accumulated over time in drilling the wells will help the company to avoid many challenges resulting in cost reduction for the project.

The use of slim holes for exploration and small-scale production of geothermal power is friendlier to the environment since there is less surface disturbance, less noise and air pollution compared to a conventional large size well. Moreover, there is less drilling fluid exposed to the surface and less heavy-duty equipment and materials used, thus minimizing the overall project cost.

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