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HIGH-TEMPERATURE GEOTHERMAL WELL DESIGN

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ABSTRACT

This paper presents methods which are used for determining the design conditions for high-temperature geothermal wells. Basic information, such as geological conditions and types of reservoirs, is presented. The emphasis is on casing design for high-temperature geothermal wells including casing loads such as collapse and burst pressures, determination of the minimum depth of casings, etc. For a "worst possible case" where no actual data is available, the boiling point curve is used. Collapse pressure is often what determines the casing wall thickness. A well simulation model can be a powerful tool for predicting the temperature and pressure along the well axis. The temperature and pressure for a flowing and a shut-in well comprises the primary basis for casing design.

1. INTRODUCTION

In designing high-temperature geothermal wells, many parameters must be considered. First are the geological aspects. High-temperature geothermal areas are mostly connected to volcanism in rift and subduction zones. The geothermal reservoirs formed are basically classified according to their temperature. The physical parameters, temperature and pressure within the reservoir, define the design criteria of geothermal wells. These are influenced by the heat source and permeability of the reservoir.

Casing designing is a major part of geothermal well design. The casing programme is defined by the number of casing strings their diameters and lengths, and wall thickness. Casing wall thickness for deep casings is determined mainly by the collapse pressure which is exerted from the cement column during the cementing operation.

There are several methods for determining the depth at which the casing shoe is set. "A rule of thumb" says that the minimum casing depth shall be one third of the total depth of the particular section of the well being drilled. The design procedures used in Iceland and New Zealand for determination of minimum casing depths are explained.

2. GEOLOGICAL CONDITIONS

Generally, high-temperature geothermal areas are mostly connected to volcanism in rift and subduction zones. Intrusions and magma chambers serve as heat sources for each high-temperature geothermal system. The surrounding groundwater approaches the heat source, is heated up and a dynamic convection system is initiated which will last as long as the fundamental parameters mentioned above exist (Figure 1). Volcanic gases participate in the chemistry of geothermal fluid and control the pH factor. Other components are dissolved from the surrounding rock. The physical parameters (temperature and pressure) are controlled by the heat source and flow of the fluid (permeability). Each geothermal reservoir has its own characteristics, but can resemble others in many ways. In the Pacific Arc, subduction volcanism is predominant; along the Atlantic Ridge, rifting volcanism is dominant. The reservoirs are built up of volcanic materials and in some cases overlaid by thick sediments (Wohletz and Heiken, 1992).

The tectonic rifts control the main flow pattern of the geothermal fluid and must therefore be carefully mapped and understood. Most of the permeability is connected to fractured rock, in the range from microfractures to fissures and fractures as observed on the surface.

3. MAIN TYPES OF GEOTHERMAL RESERVOIRS

The combination of locally variable factors like enthalpy/temperature, chemical composition, permeability distribution, depth, etc., leads to a great variety of different geothermal reservoirs. The high-temperature reservoirs have been classified into several types based on the water temperature, pressure and phases. Water can be in a liquid or vapour phase or combined as two-phase fluid. The physical properties of water and steam are very well known and are found in steam tables. Calculations on the effect of lowering the pressure can then, be easily calculated as the fluid is in a state of saturation. The following is a brief description of the main types of reservoirs as they affect

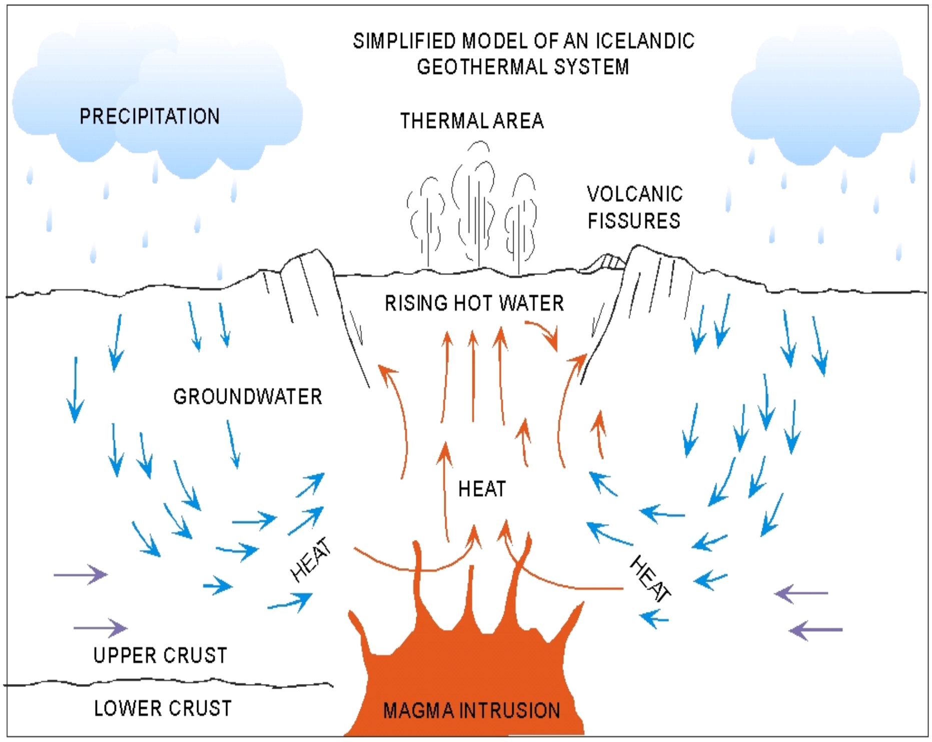

FIGURE 1 : A schematic model of a high-temperature geothermal system in Iceland (G.Ó. Fridleifsson, personal communication)

geothermal well design and the production characteristics. There are several temperature criteria used in the classifications and there seems little agreement in the literature as to what the exact temperature ranges are. The World Bank classifies the geothermal resources based on temperature as: high-temperature (>150°C), medium-temperature (100-150°C), and low-temperature (<100°C) resources.

The classification from Rybach and Muffler (1981) will, however, be used in this paper. Not only does it consider the temperature but also the phases of water found within the reservoirs as warm water reservoirs, hot water reservoirs and vapour-dominated reservoirs.

A warm water reservoir is defined as one containing water at a sufficiently low temperature (<100°C) which can be exploited for district heating, agricultural purposes and balneological use, etc. In this paper, the design of wells for warm water reservoirs will not be discussed as focus will be on high-temperature well design.

A hot water reservoir contains fluid in a liquid state in the temperature range 100-250°C. Boiling can, however, occur in hot water reservoirs in both the natural and exploited states (Figure 2). In the natural state, and especially after exploitation, boiling can occur in the reservoir due to draw-down. The two-phase zone then created is often referred to as the steam zone or steam cap. It should be remembered, however, that it contains water as well as steam, and that the pressure gradient with depth is nearly hydrostatic, but for some steam caps there is almost constant pressure until the water level is reached (Figure 3).

Depending on the depth of casing, a well can be fed both from the two-phase zone and from a deeper water zone (Figure 4). If the wells are shallow they may eventually only produce vapour as the

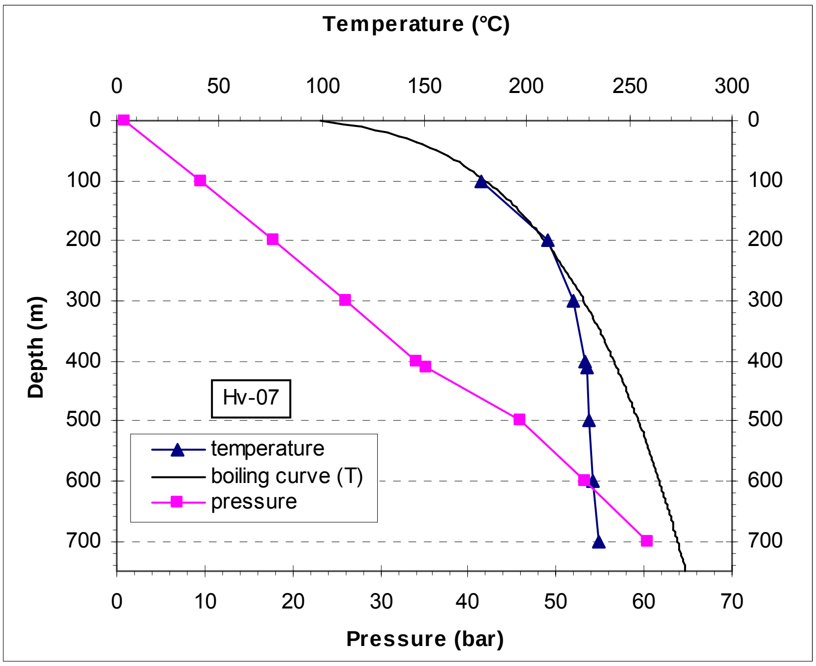

FIGURE 2: Temperature/pressure vs. depth curves for a liquid-dominated reservoir in Hveragerdi, S-Iceland

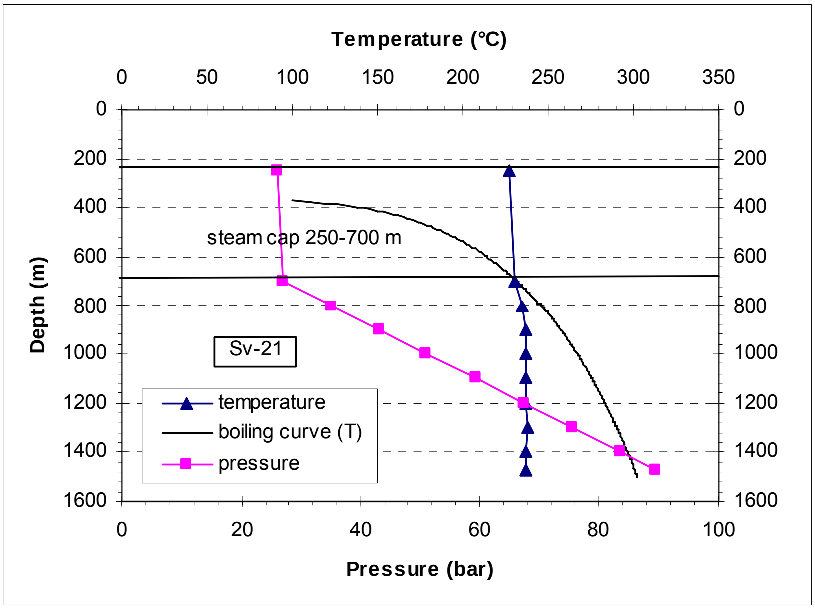

FIGURE 3: Temperature/pressure vs. depth curves for a liquid-dominated reservoir with a steam cap in Svartsengi, SW-Iceland

water level sinks below the well bottom. This transition to steam can be quite rapid and needs to be considered when designing wells, especially in fields where there has been a large draw-down.

Vapour-dominated reservoirs are full of steam. The term “vapour-dominated” was first used by D. White in 1971. The main characteristics of this system are:

(a) A discharge of steam only;
(b) The discharge comes from a region where the pressure is nearly constant with depth.

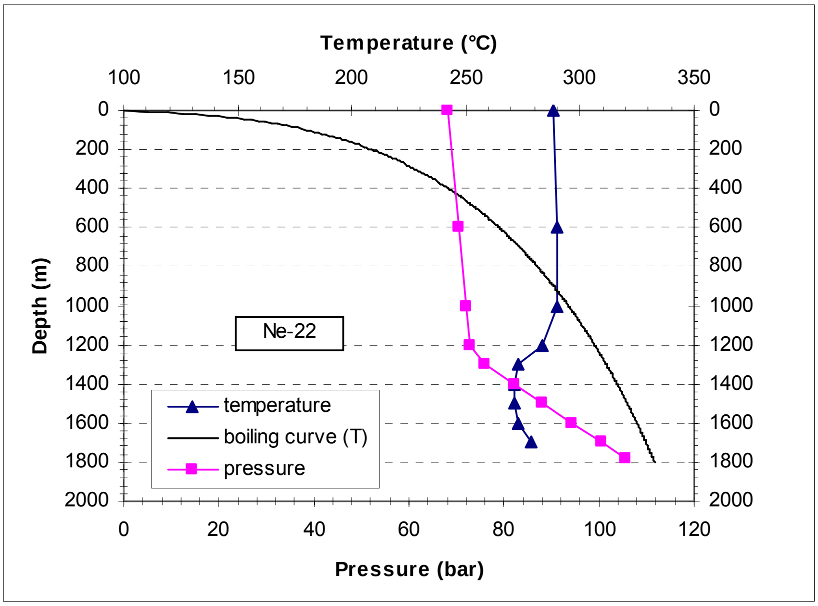

FIGURE 4: Typical temperature/pressure curves for the two-phase reservoir at Nesjavellir, SW-Iceland

The steam discharge may initially be wet, saturated or super-heated. The pressure of the production zone is usually around 33 bars, equivalent to a saturation pressure for water and steam at 235°C.

Table 1 lists basic technologies normally utilized, classified according to resource temperature.

TABLE 1: Geothermal reservoir temperatures and common technologies

Reservoir temperature	Reservoir fluid	Common use	Technology commonly chosen
High temperature - >220°C	Water and/or steam	Power generation Direct use	Flash steam Combined (flash and binary) cycle Direct fluid use Heat exchangers Heat pumps
Intermediate temperature - 100-220°C	Water	Power generation Direct use	Binary cycle Direct fluid use Heat exchangers Heat pumps
Low temperature – 50-150°C	Water	Direct use	Direct fluid use Heat exchangers Heat pumps

4. DESCRIPTION OF DRILLING TARGETS

Siting of wells considers all the available geoscientific data from surface investigations and from existing wells. The goal is for the wells to intersect permeable fractures and formations in order to extract fluids of sufficient temperature. In most cases, the target is not as well defined as, for example, in oil drilling. This is not as big a problem as it may seem, as any fluid from the formation below a certain depth can enter the well and be exploited. At this time the depth of the well is decided, within a certain range, and also the depth of the production casing. Many wells are drilled vertically but now a good portion of them are drilled as directional wells. Directional drilling is adopted to increase the accuracy of drilling operations as well as to minimize environmental impacts. Drill pads for directional drilling can be located based on one or more of the reasons presented below:

1. Topography;
2. Upflow of the geothermal fluid controlled by tectonic lineaments;
3. Distance from other manifestations;
4. Environmental impacts.

5. TEMPERATURE AND PRESSURE IN STATIC AND FLOWING WELLS

Temperature is the most important parameter that must be considered when designing the casing programme for geothermal wells. There are three important casing design considerations concerning temperature:

1. Maximum temperature along the wellbore affects other parameters such as steel type, strength, corrosion rate, scaling, pressures, thread lubricants, seal materials, cement design and cementing mechanics.
2. The static geothermal temperature profile is defined as the earth temperature along the axis of the wellbore. This set of temperature versus depth data is extremely important for casing design, often being the initial data for many design calculations.
3. The maximum change in temperature to which the casing string can be subjected. This temperature ranges between a higher temperature when the well is in a long-term flowing state and a lower temperature when it is shut-in in a long–term static condition. These temperature limits primarily affect the required steel strength and the design of the "set" stress as the casing is frozen in cement (Nicholson, 1984a).

The static reservoir temperature and pressure are interpreted from the logged heating up data of the well. Once the well is flowing the dynamic conditions can be measured by lowering a logging tool down the hole against the flow. For the first exploration wells, the temperature conditions are not known and the "worst possible case" has to be considered in the design, i.e. when the temperature and pressure distribution follows the boiling point depth curve. Lacking such data, it is possible to calculate the expected flowing well temperature and pressure profiles by well simulators or spreadsheet modelling. During flow testing the mass flow and fluid enthalpy are also determined.

6. WELL OUTPUT CURVES – MASS FLOW VS. WELLHEAD PRESSURE

The well mass flow depends on reservoir permeability, temperature, the diameter of the well and wellhead pressure. If the permeability is low it will control how much flows into the well. At times the flow is almost constant, independent of wellhead pressure (see wells Krafla 13, Bjarnaflag 11 and Nesjavellir 9 in Figure 5). This occurs mainly in two-phase reservoirs with fluids of high enthalpy. In water-dominated reservoirs the rule is: the lower the wellhead pressure, the greater the mass flow. Here the inflow performance is also a factor, but when it is very good, the diameter of the well becomes the limiting factor. Experience has shown that for very permeable reservoirs the mass flow is proportional to the cross-sectional area of the casing. In mathematical terms, this can be expressed as:

$$Q_2 / Q_1 = (D_2 / D_1)^2 \tag{1}$$

where Q = Mass flow (kg/s); and
D = Diameter of the casing (").

This means that if you increase the diameter of the production casing from 9-5/8” to 13-3/8” you can expect the mass flow to be almost twice as large (see Figure 5 for wells Svartsengi 4 with 9-5/8” casing vs. Svartsengi 8 and 11 with 13-3/8”). This relationship is important as it also allows you to “scale-up” the flow from a small diameter exploration hole to a larger size production hole (Finger et al., 1999).

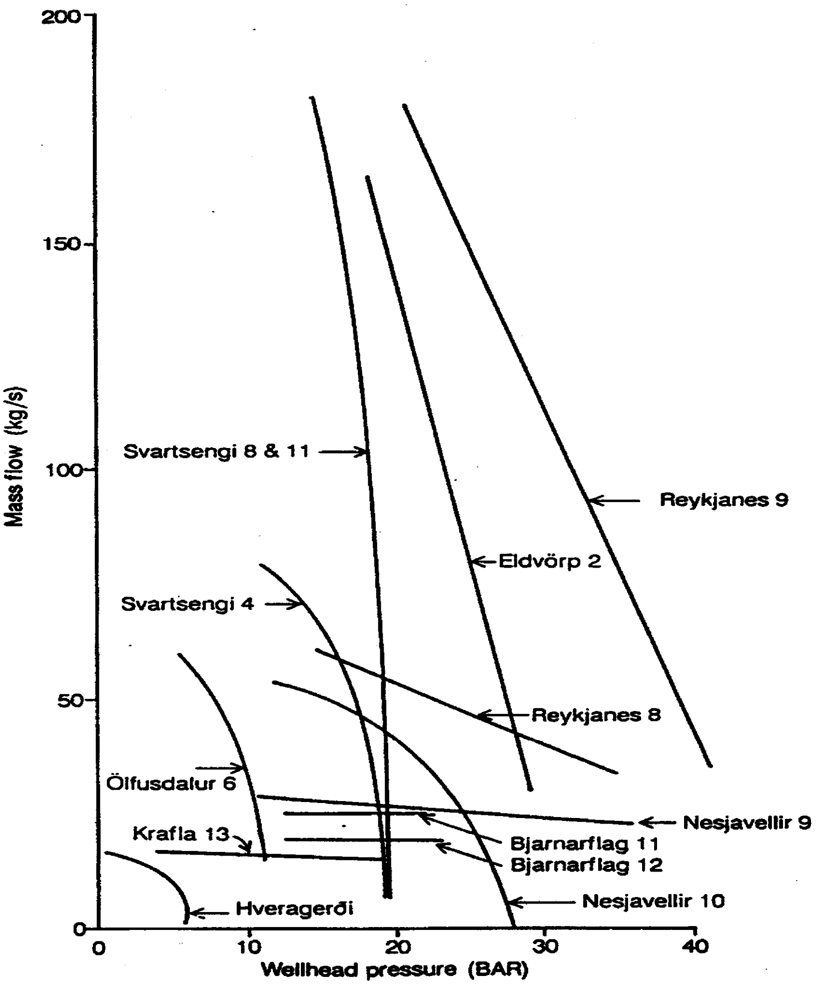

FIGURE 5: Mass flow vs. WHP for some high-temperature wells in Iceland (Thórhallsson and Ragnarsson, 1992)

7. WELL DESIGN

The design procedure for a geothermal well is similar to that of oil wells. What is different is that temperature and pressure at depth must be considered as this influences the number of casing strings and the depths to which they must be run, to provide long term safety of the well and to allow control of blow-outs during drilling. Generally, well design will follow these steps:

1. Determine the number of casing strings required and the diameter and lengths of each.
The number of casing strings and depth are determined by the geological conditions, safety requirements and at times by official regulations. Usually there are three cemented casing strings in a high-temperature well: (a) surface casing, (b) anchor casing and (c) production casing. Additionally most wells have a slotted liner that is suspended from the production casing in the open section of the hole. During preparation of the wellsite, prior to the arrival of the drilling equipment a conductor casing is usually installed to 2-6 m.

There are many factors that influence the selection of casing diameters. The main ones are well cost, rig availability and expected flow. Roughly the cost increases linearly with the diameter. The diameter of the production casing is usually decided first and then the other casing strings are selected based on the standard bit and casing sizes that give the desired clearances. Larger diameter holes are advantageous as it takes longer for scaling to restrict the flow and more repair operations can be carried out later in the life of the well. Interest has at times been shown in small diameter holes for exploration, as they are less expensive (Finger et al., 1999). The minimum diameter to which such wells can be restricted is ruled by which tools must be able to pass down the wellbore.

Typical *temperature-pressure-spinner* logging tools will fit in to almost any reasonable size hole. But if more unusual tools, for example, imaging tools such as *micro-scanner* or a *borehole televiewer* are used, the heat-shielding which they sometimes require at high temperature, defines a minimum hole size.

Core samples are sometimes used to validate a geological model of the reservoir or to assess the fracture dip, density and aperture. Diameter is not too important for this data, but sometimes a rock mechanics evaluation will need a minimum core diameter. Larger diameter cores also give better recovery in highly fractured or unconsolidated formation.

The depth limit is sometimes determined by the hook load capacity of the drilling rig (tonnes), from the suspended weight of the drill string within the hole or by the weight of casing being lowered into the hole.

2. Calculate the type and magnitude of loading: collapse, burst, and tension/compression.
When the pressure difference, dP, is larger than 0 the inside pressure is greater than the outside pressure (burst). When it is less than 0 the outside pressure is greater (collapse):

$$dP = P1 - P2 \tag{2}$$

where $P1$ = Casing inside pressure (bar);
$P2$ = Outside pressure (bar).

The greatest collapse pressure occurs during cementing of the casing. The pressure, P (bar), as a function of depth is the hydrostatic pressure calculated as:

$$P = h\rho g / 100{,}000 \tag{3}$$

where h = Depth (m);
ρ = Water or cement density (kg/m^3);
g = Gravity constant.

The cement density assumed for the high-temperature cement with silica flour and perlite is 1700 kg/m^3. Collapse pressure is exerted by the cement slurry during the cementing operation, when the inner-string method is used. The static pressures and calculated collapse vs. depth for three sizes of casing are shown in Table 2. These factors usually dictate the casing wall thickness (lb/ft). The casing strength numbers used in the Table are from the IFP Drilling Manual (Gabolde and Nguyen, 1999).

The burst pressure is the maximum inside pressure that can be expected at the wellhead whether the well is hot or cold. For hot water reservoirs, the maximum pressure is the maximum WHP during discharge. For vapour-dominated reservoirs, the maximum pressure is the steam zone pressure while the well is closed. The expected maximum pressure can be determined in several ways: (a) historic data from flowing wells, (b) assume the temperature and pressure distribution in the reservoir (the "worst possible case" is the BPD curve) and run wellbore simulators (c) for vapour-dominated wells, assume a steam-filled well from the bottom. Gases can accumulate in the production casing and depress the water level to the casing shoe, and sometimes the water level is depressed by compressed air to simulate wells to discharge.

3. Match casing strength of API casing with the requirements in step (2) after applying the appropriate safety factors.

TABLE 2: The static pressures and the required collapse resistance vs. depth; wall thickness weight (W) per unit length (L) is then selected that exceeds the collapse for three sizes of casings (Gabolde and Nguyen, 1999)

Minimum collapse resistance					**Casing 9 5/8"**		**Casing 13 3/8"**		**Casing 18 5/8"**	
Depth (m)	**Pw water (bar)**	**Pc cement (bar)**	**dP static (bar)**	**dP collapse w.saf. fac. (bar)**	**W/L (lb/ft)**	**Wall thickness (mm)**	**W/L (lb/ft)**	**Wall thickness (mm)**	**W/L (lb/ft)**	**Wall thickness (mm)**
0	1	1	0	30	36	8.9	54.5	9.7	87.5	11
100	10.81	17.68	6.87	38.24						
200	20.62	34.35	13.73	46.48						
300	30.43	51.03	20.60	54.72						
400	40.24	67.71	27.47	62.96						
500	50.05	84.39	34.34	71.20						
600	59.86	101.06	41.20	79.44			61	10.9		
700	69.67	117.74	48.07	87.68						
800	79.48	134.42	54.94	95.92			68	12.2		
900	89.29	151.09	61.80	104.16						
1000	99.10	167.77	68.67	112.40						

NB: All casings are K-55.

8. DIRECTIONAL DRILLING

There are a number of reasons for directional drilling: it may be necessary to correct an inadvertent change in hole direction, surface geographical features or boundaries may prevent the rig from being above the target, or reservoir evaluation criteria may require that the hole intercept as many high angle fractures as possible. If either of the latter two situations exist, the direction of the hole can be controlled by causing the hole to deviate from vertical at some depth.

If conventional directional drilling is planned, the principal decisions are choice of kick-off point, determination of angle-building rate and final inclination. The kick-off point is affected by many variables including formation, casing points and temperature, but it is usually fairly high in the hole for geothermal drilling, because the down-hole motors and steering tools are limited by the temperatures they can withstand (Finger et al., 1999). Now good hole cooling and procedures allow these tools to be used to total depth.

9. CASING DESIGN

The casing for a geothermal project normally represents 20-30% of the well cost. Thus, casing is a major initial well cost (Nicholson, 1984b).

Any failure of the casing string leads to loss of the well, or at least a great amount of financial load in order to re-establish the well for safe production. Therefore, the design of the casing strings is a critical part of the economics of a geothermal project (Nicholson, 1984b).

Casing string is mainly designed considering the temperature and pressure exerted from formation and/or from hydrothermal fluid within the well. In this paper casing designing is based on both temperature and different pressures. Regulatory requirements in the drilling permit will determine other aspects of the casing design and blow-out prevention equipment (BOPE). A typical specification is that surface casing is at least 10% of the total depth and that one-third of the hole be behind casing at any given time. Once the minimum required depth (presented later in detail) is reached, casing will normally be run unless the formation is particularly fractured and broken. It is important to have competent rock at the casing shoe, as it is normally required to do a pressure test by drilling out the shoe into a new formation, then applying a pressure gradient above hydrostatic pressure to the wellbore. This procedure evaluates the well's ability to withstand high pressures without breaking down the formation or the cement around the casing and is the basis for establishing the temperature to which the well can be drilled without setting another casing string. Clearly, if there is not competent rock around the shoe, the wellbore will not be able to withstand a high pressure gradient and the ability to advance the well to the desired depth/temperature will be compromised. If the minimum casing depth is reached and there is no competent rock, it is often desirable or necessary to continue drilling until a better formation is found (Finger et al., 1999).

Experience from drilling in high-temperature geothermal areas in Iceland indicates that temperatures and pressures to be expected on the well bottom may be assumed to follow the boiling curve based on the assumption of the water being at boiling conditions at any depth. This means that bottom temperature and pressure in a well of 2000 m depth may be as high as 340°C and 145 bar, respectively. At these conditions it may be difficult to design a string of casing based on the conventional requirements of keeping the casing material within the elastic limits (Karlsson, 1978).

Well casing used in Icelandic geothermal wells has been manufactured in accordance with API specifications. These specifications provide no minimum strength requirements at elevated temperatures, but tensile properties in cold conditions for various API grades of casing are presented in Table 3.

TABLE 3: Tensile requirements of casing pipe manufactured in accordance with API specification 5A

Casing grade	**Min. yield (kg/mm^2)**	**Max. strength (kg/mm^2)**	**Min. tensile stength (kg/mm^2)**	**Min. elongation (% in 2")**
H-40	28.1	-	42.2	29.5
J-55	38.7	56.2	52.7	24.0
K-55	38.7	56.2	66.8	19.5
N-80	56.2	77.3	70.3	18.5
C-75	52.7	63.3	66.8	19.5

Loads on casing in a well may be of various types and occur during the running of the casing, cementing, drilling and after completion of the well. These loads may occur both in the axial direction of the casing or in the redial direction, inwards or outwards.

Of the various possible load combinations acting on the casing string, the most critical seem to be caused by pressure and thermal expansion (Karlsson, 1978). Collapse and burst pressures are explained in detail in the following sections.

9.1 Collapse

Collapse pressure is usually found from the cement slurry column during cementing operations. There are several formulas for various ranges of D/t (diameter/thickness ratio) to calculate collapse pressure. For example, (according to Table 4), for a 18⅝" casing, *D/t* is 43. Then from Table 5 it is found that quality K-55 can be selected to set at the mentioned depth in Table 2. The formula below is used for calculating the elastic collapse pressure (API, 1989):

TABLE 4: D/t for three sizes of casings

Diameter (")	Diameter (mm)	Thickness (mm)	Diameter/thickness ratio
9 5/8	244.5	8.9	27.47
13 3/8	339.7	12.2	27.84
18 5/8	473	11	43

TABLE 5: Diameter/thickness ratio range for elastic collapse

Grade	D/t range
H-40	42.64 and greater
H-50	38.83 and greater
J-K-55	37.21 and greater
J-60	35.73 and greater

$$P_E = \frac{46.95\times10^6}{(D/t)((D/t)-1)^2} \tag{4}$$

where P_E = Minimum collapse pressure for the elastic range of collapse (psi);
D = Diameter of casing (");
t = Wall thickness of casing (").

For other ranges of D/t, the calculation can be done in the same way using a different formula.

9.2 Burst

Burst pressure is an internal pressure from fluids within the casing. Maximum burst pressure is usually when a well is shut and full of gas, or under compressed air, commonly used to stimulate the well to start flowing. The burst resistance to casings is defined by the equation (API and ISO standards; Rath, 2005):

$$P = 2ts/((D-2t)\times SF) \tag{5}$$

where P = Internal pressure (N/mm^2);
t = Thickness of pipe wall (mm);
s = Yield strength (N/mm^2);
D = Outside diameter of pipe (mm);
SF = Safety factor (generally 1.5-10.1 for bursting pressure).

9.3 Determination of minimum casing depth

The depth of the production casing is determined by how deep fluids from the colder formations need to be isolated from entering the hole and at times by the geology. One of the main determinants, however, has to do with minimum depth for safety reasons. Government regulations sometimes stipulate how deep the casings need to be run, usually to insure that the near-surface aquifers are not contaminated by cross contamination. Safety aspects are also considered. From the technical side there are four main criteria that have been applied to determine the minimum casing depth:

1. In the *New Zealand Recommended Code of Practice* the criteria is that the pressure from overburden (soil) at the last casing shoe, shall exceed the pressure from a steam filled well. Thus once the final depth of the well has been decided, the hydrostatic pressure for the BPD curve is drawn to that depth. The minimum depth of casing according to the NZ method is then found by extending the bottom hole pressure up the well, minus the steam density, until it intersects the over-burden pressure. This is then the minimum casing depth of the production casing. By repeating the same method the minimum depth of the anchor casing and then surface casing is determined (Figure 6). This method will assure that a blow-out outside the casing will not occur.

2. A method used in Iceland assumes the BPD for new fields. From well simulation studies the pressure profile for a flowing well is determined, assuming inflow at bottom. The liquid will immediately be transformed into two-phase flow up the well. The minimum depth is

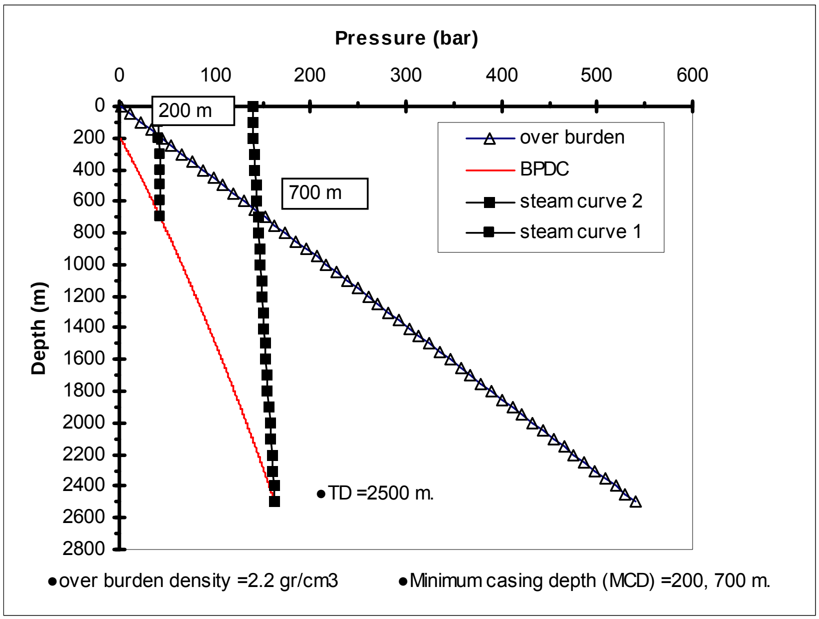

FIGURE 6: The New Zealandic method to determine the minimum casing depth for high-temperature geothermal wells

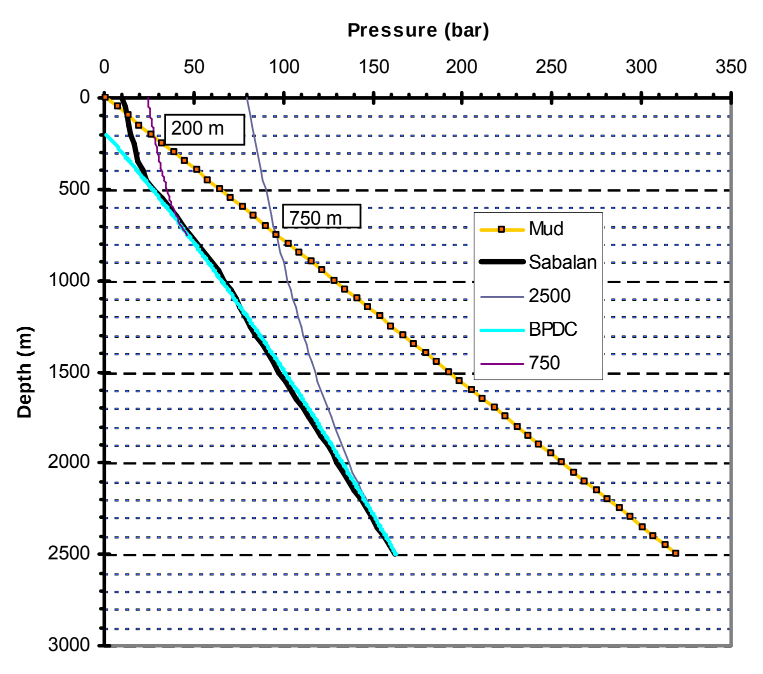

FIGURE 7: The Icelandic method to determine the minimum depth of casing using mud as blow-out preventer

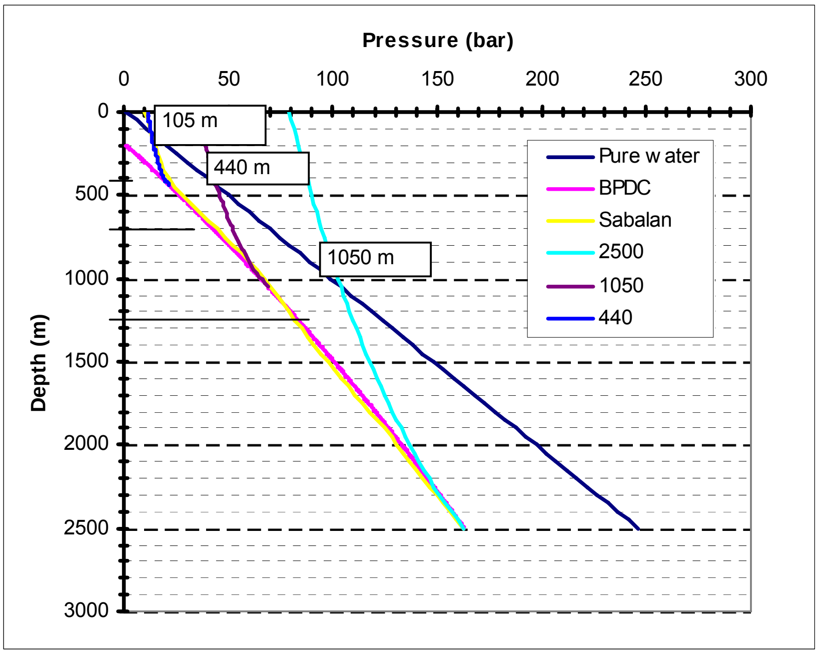

FIGURE 8: The Icelandic method to determine the minimum depth of casing using pure water as blow-out preventer

then determined by how long a column of heavy mud of 1.4 gr/cm^3 density is required to balance this pressure (Figure 7).

3. The other method used in Iceland is to consider the actual case, or most likely case, for the temperature and pressure down-hole. Then typically, the fluid only turns to two-phase flow about half way up the hole. This pressure profile is then balanced by pure water only. Pumping only water into the well insures that the drill string can be retrieved, even if there is an underground blow-out in the well (Figure 8).

It is interesting to note that the results obtained by applying these four methods lead to rather similar results for the minimum casing depth. Method 4 makes the production casing perhaps 100-200 m longer than the others. These methods mean that to reach modern day depths of high-temperature drilling, three drill strings have to be landed and cemented (surface-anchor-production). This is the general practice around the world. Conductor casings are installed when the drill site is being prepared, so the total number of casing strings is usually four.

10. CONCLUSIONS

- High-temperature geothermal wells are mostly connected to volcanic areas in rift and subduction zones. The "worst possible case" to be used as the basis for designing a high-temperature geothermal well is the boiling point depth curve.
- A well simulation model can be a powerful tool in predicting the temperature and pressure along the well axis. When actual measurements are available from existing wells the casing programme can be adapted to reservoir conditions.
- Temperature and pressure for a well, flowing or shut-in, are the most important parameters for the mechanical design of the casing.
- Collapse pressure due to cement density is often what defines casing thickness.
- Three methods to determine the number of casing strings and minimum depths are presented.

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