UNITED NATIONS
UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME
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Reports 2008
Number 11

DRILLING PRACTICE WITH AERATED DRILLING FLUID: INDONESIAN AND ICELANDIC GEOTHERMAL FIELDS

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ABSTRACT

Successful drilling is a key factor in developing geothermal fields. Drilling with aerated drilling fluid is an underbalanced drilling technique, mainly used to improve the production of wells and, in some cases, solve problems of borehole cleansing during the drilling operations. The aerated drilling technique consists of adding compressed air to the drilling fluid (mud or water). Aerated drilling fluid has a lower density than conventional drilling fluids, thus the hydrostatic pressure inside the well can be lower than the formation pressure. Using aerated drilling fluids makes it possible to reduce losses when encountering loss of circulation, which may block the formation through mud cake and decrease porosity and permeability by the infiltration of cuttings into the formation. With less formation damage, improved well production can be achieved.

When drilling and using aerated drilling fluids, the annular pressure must be controlled in order to keep it underbalanced but the differential pressure must also be minimized in order to avoid too much gain that can cause a blow out. The density of aerated drilling fluids changes at depth as a result of variable temperature and annular pressure. Determination of the annular pressure when drilling with aerated drilling fluid is important when planning the drilling program and also important during the drilling operation to make adjustments that will maintain an underbalanced state and minimize the downhole differential pressure.

The paper reviews the benefits of using aerated drilling, the ways to achieve under balanced drilling, and the equipment that is used. A model was developed to calculate the annular pressure for the full depth of the well. A chart shows how to minimize the differential downhole pressure (between annular pressure and formation pressure). Case studies of geothermal well drilling in Iceland and Indonesia are presented where aerated drilling has been applied.

1. INTRODUCTION

Underbalanced or balanced drilling is the drilling process in which the wellbore pressure is intentionally designed to be lower or equal to the pressure of the formation being drilled. This under balanced pressure condition allows the reservoir fluids to enter the wellbore during drilling, thus preventing fluid loss and related causes of formation damage. Additional equipment and special procedures are required to achieve an underbalanced drilling operation. In addition to improving well productivity by preventing fluid loss and formation damage, underbalanced drilling offers several other significant benefits that are superior to conventional drilling techniques. These include increased penetration rate and bit life, reduced probability of sticking the drill string downhole due to better hole cleaning, and reduced water requirement. This paper describes the aerated drilling procedure used for drilling high-temperature geothermal wells to achieve under-balanced or balanced drilling. A model is presented to calculate the down-hole pressures based on the air and water flows to achieve the desired downhole conditions.

1.1 History of aerated drilling

Injecting compressed air into the mud circulating system to combat circulation losses while drilling for oil was first carried out by Phillips Petroleum in Utah, USA in 1941. During the early 1970s, air or ‘Dust Drilling’ was introduced at the Geysers geothermal field in California, USA. Aerated drilling of geothermal wells was initially developed by Geothermal Energy New Zealand Ltd. (GENZL) during the period 1978 to 1982 while involved in drilling projects at the Olkaria Geothermal field in Kenya, and at the Kakkonda field in Honshu, Japan; during the later part of this period, GENZL developed its DOS based computer program “Air Drilling Simulation Package”. Subsequent aerated geothermal drilling operations occurred at the following geothermal fields as listed below (Hole, 2006):

1982 – 1987:
- North East Olkaria – Kenya.
- Aluto-Langano – Ethiopia.

1987 – 1992:
- Nigorikawa, Hokaido – Japan.
- Sumikawa, Honshu – Japan.
- Darajat – Indonesia.
- Olkaria II and Eburru – Kenya.
- Los Humeros – Mexico.

1992 – 1997:
- Los Humeros – Mexico.
- Tres Virgenes – Mexico.
- Wayang Windu, Patuha and Salak – Java, Indonesia.
- Ulumbu – Flores, Indonesia.

1997 – Present:
- Olkaria III – Kenya.
- Los Azufres – Mexico.
- Ohaaki, Mokai, Rotokawa, Putauaki, Wairakei, and Tauhara – New Zealand
- Trölladyngja – Iceland
- Hellisheidi – Iceland.
- Ulubelu, Lumut Balai – PT. Pertamina Geothermal Energy, Indonesia
- Chevron – Indonesia
- PNOC-EDC – Philippines
- Magma Nusantara – Indonesia
- Bottle Rock Energy – USA

1.2 Geothermal problems: High temperature and total loss of circulation

Geothermal well drilling operations have to cope with high temperature. In high-temperature geothermal fields, the formation temperature is usually in the range 200-350°C. Drilling mud characteristics and rheological properties will be affected by the high temperature. With increasing temperature of drilling fluids, viscosity will decrease. This condition will result in cuttings or chips not being effectively removed from the hole, instead accumulating at the bottom, increasing the risk of pipe sticking (Nur et al., 2005).

Usually, the targets of wells in geothermal drilling are faults, fractures or fissures that have high permeability and are connected with the geothermal reservoir. When drilling is in progress, drilling fluid pressure higher than formation pressure will cause a loss of circulation when these fractures are intersected. Loss of circulation in drilling operations causes poor cleaning of cuttings from boreholes that can cause pipe sticking.

When total loss of circulation occurs, drilling fluids and cuttings are pushed into the formation. It may become a problem later because the cuttings and mud cake can reduce the porosity and permeability and may reduce the production of the well. To have a total loss of circulation in the productive part of the well is highly desirable, as it indicates that the well will be a productive one. However, the loss causes some drilling problems, especially with borehole cleaning. Use of aerated drilling fluid aids in borehole cleaning, and keeps fractures open for later production.

1.3 Aerated drilling and drilling mud

Figures 1 and 2 compare conventional drilling and underbalanced drilling. The main differences between conventional drilling (using mud for drilling) and aerated drilling as one of underbalanced drilling procedures are shown in Table 1.

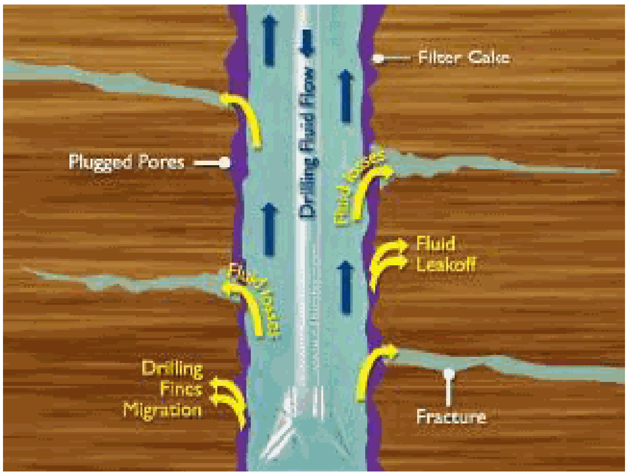

FIGURE 1: Conventional drilling (Zwager, 2007)

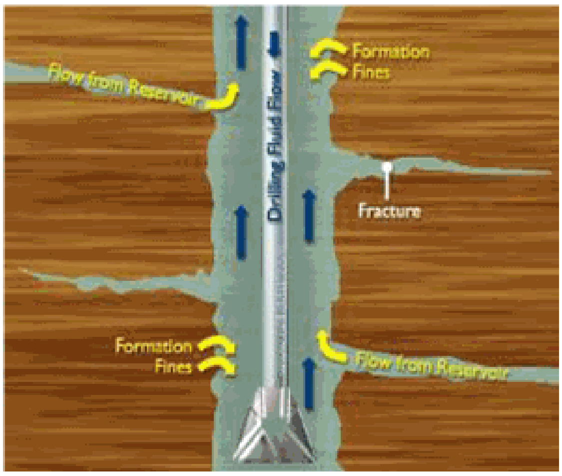

FIGURE 2: Underbalanced drilling (Zwager, 2007)

1.4 Benefits in using aerated drilling fluid

The use of aerated drilling fluid has been reported to produce the following benefits:

1. Reduction of formation damage and increased production of wells. In the drilling operation, aerated drilling fluid, which has a lower density than water, can have hydrostatic pressure lower than the formation pressure which can minimize the loss of drilling fluids and cuttings to the formation. Despite low density the aerated drilling fluid has the properties to raise the cuttings

TABLE 1: Comparison between using aerated drilling fluid and mud

	Aerated drilling	**Mud drilling**
Formation damage	Aerated drilling reduces the probability of formation damage because the borehole pressure is less than the formation pressure; drilling fluids and cuttings do not go into the formation. Cuttings pushed into the formation can block and reduce porosity and permeability.	Can cause formation damage when mud cake forms in the production zone and drilling fluids and cuttings go into the formation when total loss of circulation occurs, blocking permeability.
Rate of penetration	Drilling with underbalanced drilling increases the rate of penetration because of improved bit performance and reduces the regrinding of cuttings. Penetration rates, experienced in the basaltic lavas encountered in Icelandic geothermal field, have been as much as three times the penetration rates experienced in the same formations drilled conventionally (Hole, 2006).	Rate of penetration lower than when using underbalanced drilling.
Controlling hole pressure	Aerated drilling fluid has lighter density thus leads to lower annular pressure than formation pressure. It is flexible in controlling formation pressure as pressure in annulus can be maintained by reducing the pressure at the throttle valve at the flow line and air and liquid ratio.	Drilling mud has higher density than aerated drilling fluid. Hydrostatic pressure depends on the density of the mud.
Loss of circulation	Aerated drilling has a lower density than water that can work against circulation loss. When using aerated drilling fluids, even formation pressure is low, but it still has the possibility to deliver cuttings to the surface. A hydraulic gradient towards the wellbore, using under-balanced drilling will reduce the invasion of fluids and fine grained cuttings into the production zone (Bjelm, 2006).	When a total loss of circulation happens, drilling with mud is changed into blind drilling (drilling only with water). The water still enters the formation and the cuttings are not delivered to surface, which can increase the probability of pipe sticking due to poor cleaning of the borehole.
Annular velocity	Aerated drilling needs higher annular velocity to raise the cuttings.	Lower annular velocity.
Volume of water requirement	It needs less water due to the reuse of water and less water loss to formation.	Needs more water when drilling in geothermal fields.
Drilling fluid materials	Water, air, foaming agent, corrosion agent, and other chemical solutions.	Water, bentonite, and many additives to preserve the quality of mud; depends on bottom hole conditions.
Extended equipment	Needs additional equipment than for conventional drilling: air compressors and booster to compress air, mist pump, separator etc.	Mud tank, hopper, mud pump.
Cost	Daily compressors, booster rent costs and fuel.	Cost of drilling mud.
Operation	Needs a skilled person to operate aerated drill. There are differences in jointed or disjointed drill string operations because of the high pressure of aerated drilling and the need to maintain the pressure. Check valve is needed to put in a drill string.	Check valve is put at the bottom of the drill string; operation as conventional drilling.
Corrosion	Causes somewhat higher drill pipe corrosion.	Less drill pipe corrosion

and deliver them to the surface. The formation damage (mud cake or a decrease in porosity and permeability by the infiltration of cuttings into the formation) can be avoided. Examples are given in Table 2 below for wells drilled in Kenya.

2. Underbalanced drilling using aerated fluids can increase the penetration rate. A reduction in differential pressures between the hole and the formation, caused by use of lighter weight fluids, would be expected to increase penetration rates because of improved bit performance and the reduction in regrinding cuttings. This increase in penetration is frequently found in practice. It has the added advantage of returning larger cuttings which can be used for better geological examination (Russel, 1987).
3. Longer bit life. Aerated drilling fluid cools the bit and reduces the regrinding of cuttings and increases the rate of penetration. This means fewer bit changes.
4. Aerated drilling fluid can reduce differential sticking.
5. Less water requirement because aerated drilling fluid reduces loss of circulation and reuses water or mud from the separator after cleaning.
6. The temperature recovery of wells drilled with aerated drilling fluid is significantly faster. Wells drilled through 'blind drilling with water' usually experience a significant recovery heating period after completion of the well. The large volumes of water lost to the reservoir can take a long period to heat up.

TABLE 2: Comparison of thermal outputs of wells drilled with and without aerated fluids at Olkaria, Kenya (Hole, 2006)

Drilled blind with water		**Drilled with aerated fluid**	
Well no.	**Output (MWt)**	**Well no.**	**Output (MWt)**
1	43.31	A-1	37.05
2	12.75	A-2	98.73
4	22.15	A-4	58.86
5 (drilled with mud)	14.76	A-5	105.49
6	21.38	B-1	27.59
		B-3	36.26
		B-7	32.72
		B-9	67.63
Average	**22.87**		**58.04**

2. AERATED DRILLING EQUIPMENT AND LAYOUT

Underbalanced drilling with aerated drilling fluids requires more equipment than conventional drilling with mud or water, as will be described.

2.1 Equipment

Additional equipment needed when using aerated drilling fluids includes the following:

- Compressors for the first stage of compressing the air;
- Booster for compressing the air to the final pressure;
- Mist pump for injecting small amounts of foaming agent, corrosion agent, and other chemical solutions into the standpipe, downstream of the booster compressor;
- Special rotary head, banjo box, throttle valve and a line to the separator;
- Separator for air/steam/water. The air and steam is vented from the top of the separator to the atmosphere but the water or mud is returned to the system;
- Float valves are applied in the drill string and near the bit.

In Table 3 are examples of equipment used in a drilling operation in Indonesia through an air package from Air Drilling Associates Inc. and its specifications.

TABLE 3: Extended equipment used for aerated drilling fluid (from Air Drilling Associates, Inc.)

Item	Description	Quantity
1	Sullair 1150 XH silenced air compressors. Each with a maximum continuous output of 1150 scfm at 350 psi	3
2	Joy WB-12 booster. Maximum continuous output: 2700 scfm at 2500 psi	1
3	National J-80 mist pump Required for injecting foam solution for mist and/or foam drilling. Capable of injecting 46 gpm (gallons per minute) fluid up to 2633 psi	1
4	Air injection metering (pressure, temperature, flow rate)	1
5	Delivery line 2” 3000 psi	75 m
6	Rig floor manifold. In order to bypass delivered air and blow down standpipe pressure	1
7	String float subs, locking subs & type G valves	5
8	Pressure release tool	1
9	Jet sub & replacement jets	1
10	Washington Series 1500 geothermal rotating control head 13⅝” 3M bottom flange.	1
11	10” Blooie line c/w class 150 flanges	50 m
12	Blooie line silencer/diffuser	1
13	Lighting for equipment	1 set
14	Field office & workshop (20’ ISO)	1
15	Rig-up container (20’ ISO)	2
16	Spare parts for six months in a remote location	1 lot

Necessary air flow rate can be obtained by combining 3 Sullair 1150XH air compressor (350 psi delivery pressure) with an additional compression by Joy WB-12 booster which reaches a maximum pressure of 2500 psi. This basic air package used in Indonesia produces an average 2700 scfm (standard cubic feet per minute) at 2500 psi, i.e. using:

- 3 x Air compressor, Sullair, 1150/350 with a capacity of 2700 scfm;
- 1 x Booster, Gardner-Denver Joy WB-12 with a capacity of 2500 psi;
- 1 x Mist pump, National J-80 with a capacity of 2500 psi.

2.1.1 Compressor

A typical air compressor is shown in Figure 3. Reduced oxygen when working at an elevation above sea level affects the capacity of the compressor. Usually compressor capacity reduces by 3% for every 300 m elevation above sea level (Zwager, 2007). For example, at 1500 m (4950 ft) above sea level, compressor capacity is reduced by 15%, or 2932 scfm.


FIGURE 3: The air compressor

The Sullair 1150XH silenced air compressor has the following specifications:

Compressor:

- Direct drive, two stage helical screw compressors;
- Rated 1150 scfm at 350 psi at STP;

- Rerated 3% / 300 m elevation. 150-350 psi deliverable following cooling and scrubber,
- Pressure selector low/high, 0-100% capacity control, automatic loading and unloading;
- Full control panel with protective shutdowns;
- Quiet operating – meets US EPA sound requirements of 76 dBA at 7 metres.

Compressor engine specifications:

- Powered by Caterpillar C-15 four cycles, turbocharged diesel engine;
- Rated 500 BHP @ 1900 RPM;
- Approximate fuel consumption (at full load) = 18 gal. fuel per hour.

Dimensions:

- Weight = 17,500 lbs, Width = 8’, Length = 19' 6”, Height = 8' 6";
- Oilfield skid mounted.

2.1.2 Booster

The Joy WB-12 booster (Figure 4) has the following specifications:

Booster:

- Double-acting, reciprocating, inter & after-cooled two stage pressure booster;
- Suction pressure range 300 to 500 psi;
- Maximum frame horsepower 300 HP @ 700 rpm;
- Maximum volume single-stage: 3700 cfm to 800 psi;
- Maximum volume two-stage: 2700 cfm to 2500 psi.

FIGURE 4: The booster

Engine:

- Powered by Caterpillar C-16 ATAAC, four-cycle, turbocharged air to air after-cooled;
- Tier 2 certified & stage II certified diesel engine. Protective engine and compressor shutdown system, 24 V light package with spark arresting muffler;
- Rated 608 BHP @ 2100 rpm;
- Approximate fuel consumption = 14 - 22 gal. per hour.

Dimensions:

- Weight = 32,280 lbs. In Heli-lift situations the engine and after cooler can be removed to reduce the skid weight to less than 20,000 lbs;
- Width = 8' 2", Length = 22', Height = 10’1”;
- Oilfield skid mounted with load certified lifting rack with 24 V light package;
- Environmentally seal-welded skid with containment rail and drains.

2.1.3 Mist pump

FIGURE 5: Mist pump

Air Drilling Associates, Inc. use the National J-80 triplex liquid injection pump (Figure 5) for injecting small amounts of foaming agent, corrosion agent, and other chemical solutions into the standpipe, downstream of the booster compressor. It has the following specifications:

Pump:

- Single acting triplex liquid injection pump;
- Rated for 2633 psi at 46 gpm w/ 2” plungers;
- Four speed transmission;
- Two x 20 bbl. Stainless steel tanks;
- Maximum frame horsepower 60 BHP at 500 rpm.

Engine:

- Powered by Caterpillar 3054 DIT, 4 cycle diesel turbocharged engine;
- Rated 105 BHP at 1800 rpm;
- Approximate fuel consumption = 4 gal. per hour.

Dimensions:

- Weight = 12,500 lbs., Width = 7' 4", Length = 22', Height = 7' 4";
- Oilfield skid mounted;
- Environmentally seal-welded skid with containment rail and drains.

2.1.4 Geothermal steam separator / silencer

Figure 6 shows a typical aerated drilling separator. It should have the following specifications:

- Allowing steam to flash safely;
- Cuttings and fluid underflow is returned to shale shakers;
- Flow can be directed either to separator or directly to the sump.

FIGURE 6: Aerated drilling separator

2.1.5 Rotating head and float valve

The Washington Series 1500 (Low Pressure Applications) rotating head (Figure 7) is designed to seal off the drill string components continuously and to divert all cuttings and debris away from the rig. It is available in various flange sizes, typically either 13-5/8”, 20”, or 26-1/4”. The maximum height (A) of the unit is usually less than 36” (915 mm). A rotating control head is not a blow-out prevention tool, but intended solely for sealing around the drill pipe and diverting wellbore returns away from the rig floor. No API/IADC standards exist for pressure testing rotating control heads and, thus, caution is advised whenever high pressures (over 250 psi for this model) are exerted on the rotating control head sealing elements. Special types of rotating head sealing elements (rubbers) exist for different applications, e.g. regular, geothermal, and those resistant to hydrocarbons.

FIGURE 7: Washington rotating head

Float valves (Figure 8) are used to prevent back flow up the drill string from pressured air drilling, hot fluid and steam from well or air drilling pressure itself to the rig floor through a drill string during connection of a new drill pipe. In conventional drilling, usually a float valve is located above the drill bit, preventing flow (blow out) through the drill string and preventing plugging of the bit by halting any backflow of cuttings into the string during connections. Because air drilling has pressure, at least one string float valve is run in the drill string to prevent back flow from the drill string to the rig floor during connection and to decrease the connection time by keeping the aerated mixture pressurized below the top float valve. The check valve is located in the drill string close to the surface and once it has lowered to 100-200 m as the drilling progresses, it is moved up in the string.

FIGURE 8: Float valves

Additionally, during a connection when injection is stopped, the bottom hole pressure initially decreases due to the frictional pressure loss. Then, during the connection time, due to buoyancy and inertial forces, the gas phase continues moving upwards while the liquid phase flows backwards. This fluid separation forms liquid slugs in the annulus and inside the drill string. Upon restarting injection and regaining circulation, frictional pressure is exerted on the bottom hole and the liquid slugs in the drill string are pumped into the annulus, thus increasing the hydrostatic pressure. Consequently, during a pipe connection, a pressure spike is observed with a short period of sustaining higher bottom hole pressure that usually exposes the formation to overbalanced conditions. Sometimes float valves are inserted into the drill string approximately every 300 m (984 ft). After implementing this new procedure for making pipe connections, the BHP was almost always maintained below the reservoir pressure and the BHP fluctuations are as high as 3.45 MPa (600 psi) (Perez-Tellez, 2003).

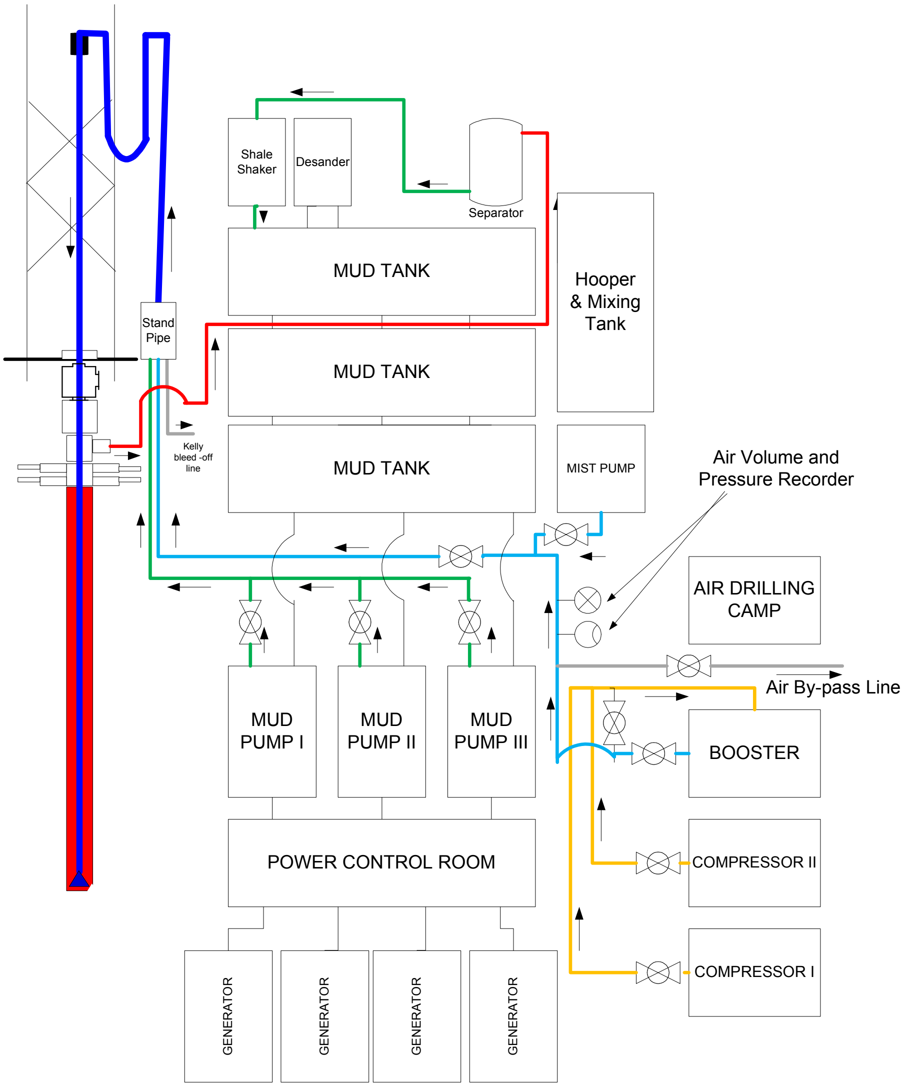

FIGURE 9: Aerated drilling layout at Hellisheidi

2.2 Aerated drilling layout

The drilling layout of the air equipment used for drilling at Hellisheidi geothermal field in Iceland is shown in Figure 9. The drilling rig is of the type Drillmec HH-300 with an automatic pipe handling system for single joints, thus the monkey board is no longer necessary. The drill pipes are stored vertically in cradles near the rig floor. The pipe handling is operated by one person on the rig floor with remote control by the driller in the driller's cabin. This rig uses a hydraulic top drive to rotate the drill string. Iron roughneck is used to connect and disconnect drill pipes with a fully automatic operation (hands-off technology) leading to a safer and more stable process of connecting and disconnecting the drill pipes (Binder, 2007). The mud pumps are driven by an electric motor. The drilling operation in Hellisheidi uses mud as the drilling fluid until the production casing is cemented; after that it uses aerated water while drilling the production zone. Adjustments are made in water and air flow rates and the down hole pressure is also affected by throttling a valve on the blooey line.

As shown in the layout in Figure 9, the air is first compressed by two screw compressors, with the final compression done in the booster. After that the compressed air flows into the standpipe manifold and is mixed with water from the mud pumps and circulates through the drill hose and down the drill string. From the bottom hole at annulus, the aerated drilling fluid will return to the surface carrying the cuttings to the separator. In the separator, air will be separated from the aerated drilling fluid. The fluid and cuttings then go to the shale shaker to separate the cuttings from the fluids. The fluid is cleaned further by removing sand or fine grains in the desander/desilter. Some tools are installed in the air line from the booster such as a pressure gauge and the flow rate monitor. The data of air pressure and flow rate are sent to the control panel for the driller, tool pusher and air drilling engineer.

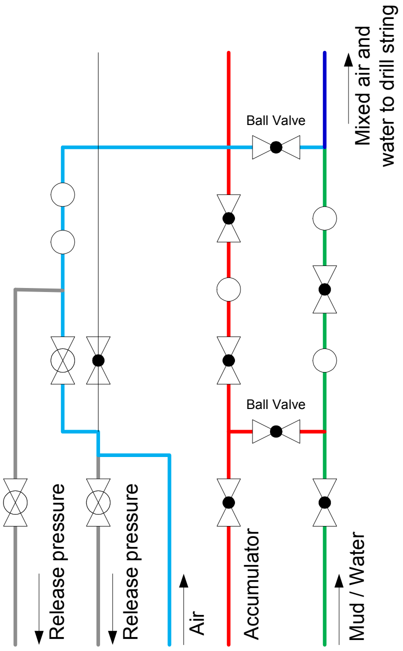

FIGURE 10: Standpipe manifold

On the line from the booster to the standpipe there is valve for closing and opening the aerated drilling fluid to the standpipe manifold. There is also a ball valve which is used to release the pressure when the valve to the standpipe manifold is closed. Figure 10 shows the manifold by the driller's cabin which is used to open and close the air line e.g. when a new drill pipe is added. The air flow to the drill string is stopped temporarily and is vented though a pressure release. This way, the operation of the air compressors is not interrupted while adding a new drill pipe.

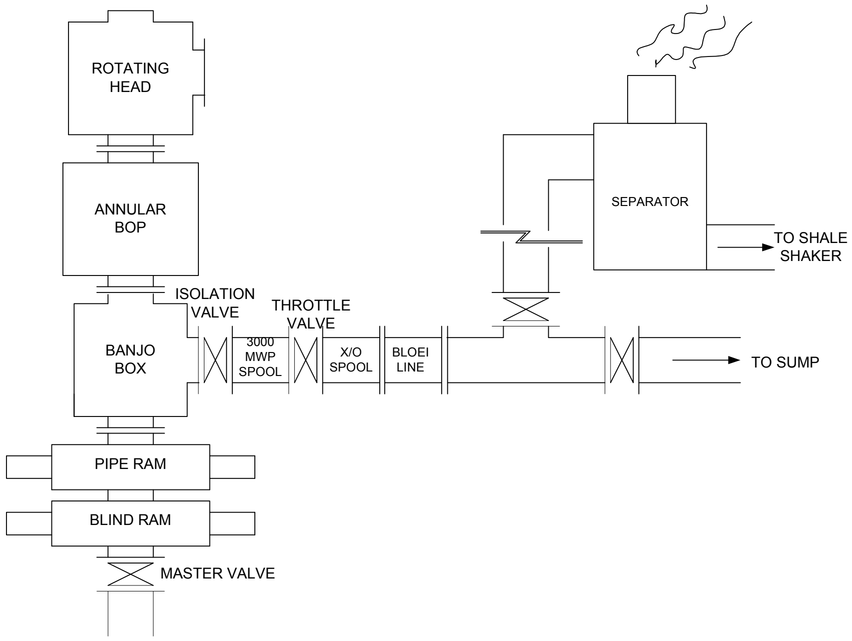

FIGURE 11: Blow out preventer and flow line setup

Figure 11 shows a blow out preventer and flow line that usually is set up during drilling when using aerated drilling. When drilling geothermal wells with aerated drilling fluids, the intent is to drill the well with well bore pressure close to balance. Instead of losing vast amounts of water ("blind" drilling) into the formation, the compressed air that is injected along with the water is circulated back up the annulus and heats up significantly on the way. In addition, sometimes an under-balanced drilling condition can exist which can cause some hot water to enter the wellbore from the reservoir. The hot water returns can sometimes be in excess of 150°C (but are though typically kept below 100°C) and need to be kept away from the rig floor. Rather than flow through the rotating control head, the return flow is taken through a flow tee called a “banjo box” that is placed between the rams and the annular preventer. Another reason to keep the returns away from the rotating control head is that they will very quickly erode the rubber rotating head sealing element.

In order to keep the well under control, the return flow is adjusted with a “Throttle Valve”, a wedge gate valve with hard faced seats of Stellite. As the heated returns pass through the choke, the resultant pressure drop causes the water to flash into steam if the temperature is above the boiling point. The steam/air separator contains the energy released when the steam expands, and the water and cuttings are returned back to the shale shakers.

3. PRESSURE LOSS IN DRILL STRING AND ANNULUS

Drilling fluids flowing through a pipe loose energy which is absorbed by dissipation in friction forces:

1. Internal friction due to viscosity;
2. External friction due to pipe roughness.

This loss of energy is called the pressure drop or loss, and is expressed by the pressure of the fluid between two points of the pipe. For example, a circulating drilling mud has an initial energy represented by the pump discharge pressure. This energy will be totally lost in the mud circuit because the mud pressure is zero when it returns to the pits. In this case, the pump discharge pressure represents the total pressure loss in the mud circuit (Gabolde and Nguyen, 1991).

These pressures losses occur:

1. In the surface equipment;
2. In the drill pipe and drill collar;
3. Through the bit; and
4. In the annulus between the well bore and the drill string.

The pressure loss equations are a function of:

1. Flow rate;
2. The rheology of the fluid; and
3. The pipe and hole geometry (diameter)

The total pressure is the sum of the frictional pressure drop and static pressure difference (caused by density differences). By comparing the estimated total pressure that should occur and the actual pressure during the drilling operation, we can see if there are problems such as: leakage at the drill string, lost circulation of drilling fluids, pipe sticking, and whether the pressure is underbalanced or overbalanced.

3.1 Formation pressure

Information on formation pressure and the temperature of wells to be drilled is very important for any drilling operation. Usually formation pressure and temperature from the latest wells are referenced as the formation pressure is usually not so different between wells in the same field and with the same well target. The formation pressure and temperature can also be obtained from well testing when a drilling operation is in progress or after a drilling operation.

During an underbalanced drilling operation, the hydrostatic pressure from aerated drilling fluids should be intentionally maintained lower than formation pressure to avoid losses of drilling fluids to the formation and/or control gain from the formation. Information on the formation temperature is used to calculate the circulating temperature of the drilling fluid. Information on circulation temperature is important as the density of the air is a function of temperature and pressure. An example of formation pressure and formation temperature can be seen in Figure 12 (well HE-46 at Hellisheidi).

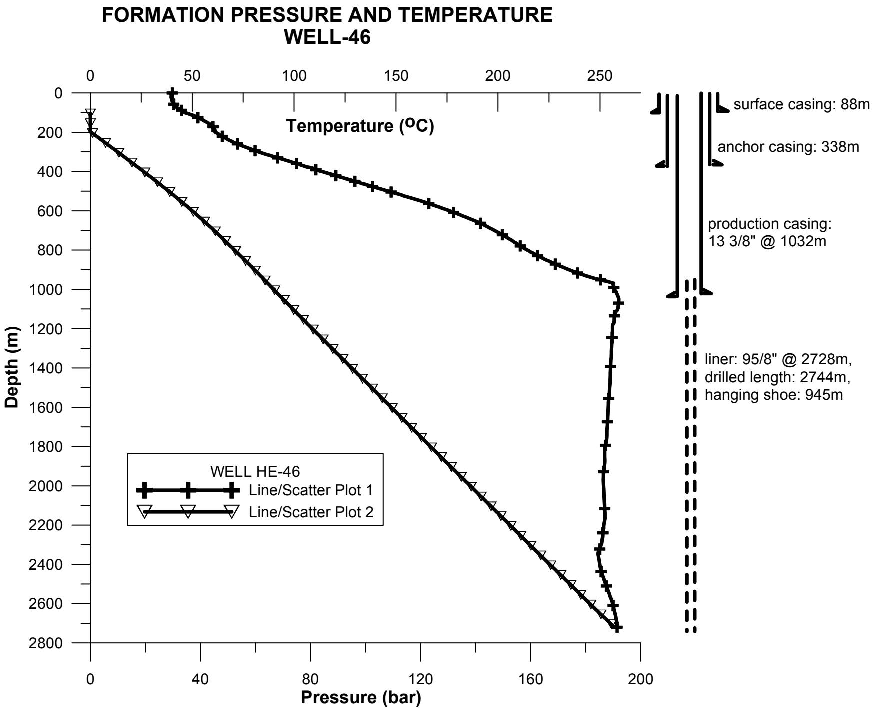

FIGURE 12: Formation pressure and temperature of well HE-46

3.2 Calculation model of pressure losses in drill string and annulus

The model presented here calculates the frictional pressure drop for the mud in the annulus and drill string based on equations in the Drilling Data Handbook (Gabolde and Nguyen, 1991). The static pressure is affected by the fluid density. Calculation of the fluid density is highly influenced by the air-water ratio and by the static pressure at each depth as the air bubbles are compressed deep in the well. Another model is required to calculate the circulation temperature down the drill string and up the annulus as the temperature affects the air density. The drilling fluid circulation temperatures that are used here result from a model called STAR that was developed by Mr. Sverrir Thórhallsson and Dr. Árni Ragnarsson of Orkustofnun in the year 2000. The STAR model calculates temperature profile of circulating drilling fluids based on heat flow from the formation to the annulus, and heat exchange between the annulus and the drill pipe (Huang Hefu, 2000). An example is seen in Figure 13.

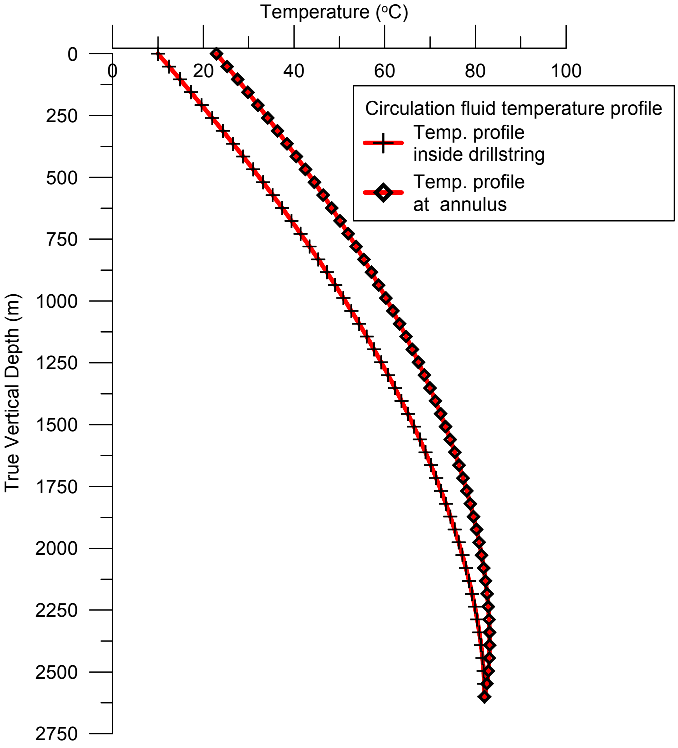

FIGURE 13: Temperature profile output by STAR model

These are the basic equations used in the model calculation of pressure in the annulus and inside the drill string. The spreadsheet model uses Microsoft Excel which divides the well depth into elements. The starting point is the pressure of the fluid returning to the surface, as that is often controlled (say 1-3 bars). Knowing the water and air flow rates, the spreadsheet model calculates the static pressure at each depth all the way back to the surface, which then is the standpipe pressure. By comparing the calculated static pressure with the reservoir pressure, one can adjust the air-water flow and backpressure to achieve the desired pressure balance or underbalance.

The pressure losses have the form:

$$p = NB \tag{1}$$

Calculation for N in the drill string is given by:

$$N = \frac{LQ^{1.8}}{901.63D^{4.8}} \tag{2}$$

Calculation for N in the annulus is given by:

$$N = \frac{LQ^{1.8}}{706.96(D_0 + D_i)^{1.8}(D_0 - D_i)^3} \tag{3}$$

where p = Pressure loss (kPa);
N = Pressure losses for pure water;
B = Coefficient corresponding to circulating mud;
D_o = Annulus outside diameter (in);
D_i = Annulus inside diameter (in);
Q = Drilling fluid flow rate (l/min);
L = Length of drill string (for N in drill pipe, L is the length of the drill pipe for the drill collar and surface equipment) (m).

The coefficient B corresponding to circulating mud is given by the equation:

$$B = d^{0.8}\mu_p^{0.2} \tag{4}$$

Pressure losses in bit P_{dbit} is given by:

$$p_{dbit} = \frac{dQ^2}{2959.41x(0.95)^2 A^2} \tag{5}$$

Total of pressure losses p_{total} is given by:

$$p_{total} = (N_1 + N_2 + N_3 + N_4 + N_5)B + p_d \tag{6}$$

where d = Specific gravity (kg/l);
μ_p = Plastic viscosity (cP);
A = Area of nozzles (in^2);
N_1 = Pressure loss coefficient in the surface equipment;
N_2 = Pressure loss coefficient in the drill pipe;
N_3 = Pressure loss coefficient in the drill collar;
N_4 = Pressure loss coefficient in the hole/drill collar annulus;
N_5 = Pressure loss coefficient in the hole/drill pipe annulus.

The input for the calculations is:

1. Properties of air
   - Flow rate (scfm).
2. Properties of water:
   - Flow rate Q (l/min);
   - Specific gravity.
3. Properties of mixed water and air:
   - Temperature (°C).
4. Information of surface equipment:
   - Size and length of stand pipe;
   - Size and length of drill hose;
   - Size and length of Kelly;
   - Size and length of swivel.
5. Information of drill string:
   - Outside diameter (D_o) and inside diameter (D_i) of drill pipe;
   - Outside diameter (D_o) and inside diameter (D_i) of drill collar;
   - Diameter of bit nozzles.
6. Information of annulus:
   - Diameter of borehole.
7. Pressure at output.

Steps of calculation:
The calculation is made using a Microsoft Excel table where the borehole is divided into 5 m sections. In the first row, the calculation of pressure starts at the annulus, then it continues from the surface to the bottom of the hole and then at the bit, back through the drill string, and to the surface. For the first row it becomes:

1. Calculate the pressure loss coefficient, N (bar/depth) at annulus/depth, where the input is a mixture of water and air, diameter of the hole and the outside diameter of the drill pipe:

$$N = \frac{LQ^{1.8}}{706.96(D_0 + D_i)^{1.8}(D_0 - D_i)^3} \tag{7}$$

2. Assume that the pressure drop at the output at the surface is set at 1 bar-a.
3. Calculate the density of air (kg/m^3):

$$d_{air} = \frac{1000 \times P_{anullus}}{2.9667770745256 \times T} \tag{8}$$

where d_{air} = Specific gravity of air (kg/m^3);
$P_{annulus}$ = Pressure in annulus (bar);
T = Temperature (K).

4. Calculate density of 2-phase mixture (kg/m^3) by hole diameter, water/mud (kg/m^3 and l/s), air (kg/s), and air (kg/m^3). Density of mixed water and air varies at depth:

$$d_{2phase} = \frac{(d_{water,mud} * Q_{mud,water}) + m_{air}}{Q_{mud,water} + \dfrac{m_{air}}{d_{air}}} \tag{9}$$

where d_{2phase} = Specific gravity of aerated drilling (kg/m^3);

$d_{water,mud}$ = Specific gravity water or mud (kg/m^3);
$Q_{mud,water}$ = Flow rate of mud or water (m^3/s);
m_{air} = Mass flow of air (kg/s).

5. Calculate the volumetric flow of aerated drilling fluid, Q_{mix} (l/s):

$$Q_{mix} = \left(\frac{m_{air}}{d_{air}}\right) \times 1000 + Q_{mud,water} \tag{10}$$

For the second row it is:

1. Calculate *N:*

$$N = \frac{LQ^{1.8}}{706.96(D_0 + D_i)^{1.8}(D_0 - D_i)^3} \tag{11}$$

where Q = Q_{mix} from 1st row.

2. Calculate the pressure:

$$p_{losses} = (N_1 + N_2 + N_3 + N_4 + N_5)B + p_d \tag{12}$$

$$B = d^{0.8}\mu_p^{0.2} \tag{13}$$

$$P_{annulus(n)} = P_{annulus(n-1)} + P_{losses} + d_{2phase} * g * \Delta_h \tag{14}$$

where d = d_{2phase} from 1st row;
μ_p = Plastic viscosity (cP), assume it is set at 1 bar-a;
p_d = p bit, has only a value at the bit;
n = Row.

3. Calculate the density of the air (kg/m3):
4.

$$d_{air} = \frac{1000 \times P_{annulus}}{2.9667770745256 \times T} \tag{15}$$

where T = Circulation fluid temperature (from STAR model)

5. Calculate density of 2-phase mixture (kg/m^3) by hole diameter, water/mud (kg/m3 and l/s), air (kg/s) and air (kg/m^3). Density of mixed water and air at annulus varies with depth:

$$d_{2phase} = \frac{(d_{water,mud} \times Q_{mud,water}) + m_{air}}{Q_{mud,water} + \frac{m_{air}}{d_{air}}} \tag{16}$$

where d_{air} = Specific gravity of air (kg/m3) from 2nd row.

6. Calculate the volumetric flow, Q_{mix} (l/s):

$$Q_{mix} = \left(\frac{m_{air}}{d_{air}}\right) \times 1000 + Q_{mud,water} \tag{17}$$

The result from the model calculation is a full pressure profile of the annulus, bit, drill string and surface equipment. Additional results include the density of aerated drilling fluid at depth, annular velocity and the difference between annular pressure and formation pressure. The inputs to the calculation model can be changed for different flow rates and different back pressures set at the flowline, resulting in a different pressure profile at the annulus. We can do the same in the field to maintain the annular pressure which is still in an underbalanced condition, thus minimizing the differential pressure between annulus pressure and formation pressure.

A simulation of the calculation model was done to find the pressure profile at the annulus and drill string, using two different drilling fluids: aerated drilling fluid and mud. This profile was then compared with the formation pressure to obtain the differential pressure between the annular pressure and the formation pressure. The casing design for the calculation was:

- Production casing reaches from surface (0 m) to 847.6 m depth;
- The borehole has a diameter of 12¼" from 847.6 to 2600 m depth;
- The used drill string has an assumed DP 5" with an outside diameter D_o = 5" and an inside diameter D_i = 4.67", and the length = 2500 m;
- DC are 8" with D_i = 3.5" and a length of 100 m;
- The bit has no nozzles.

Inputs for aerated drilling fluids assumed in this model are:

- Flow rate of air is 1700 scfm;
- Flow rate of water is 55 l/s;
- Backpressure at flowline is 1 bar;
- Circulation temperature is taken from the STAR model.

The input for the mud is:

- The flow of mud is 55 l/s;
- Its specific gravity is 1030 kg/m^3.

Figure 14 shows that mud drilling fluids have greater annular pressure than formation pressure while for aerated fluids annular pressure is less than formation pressure. Figure 15 shows an underbalance pressure with aerated drilling, but overpressure if mud/water only is used.

Figure 16 shows the different annular velocities of the two drilling media. The density of aerated drilling fluid in annulus varies with depth. At the bottom of the hole where the hydrostatic pressure is highest, the air component is highly compressed and therefore the density of the fluid is highest there. From the bottom of the hole upwards, when the pressure column of the fluids becomes less, the air expands thus reducing the average fluid density (Thórhallsson, 2008). The density of aerated drilling varies with depth as shown in Figure 17.

3.3 Maintenance with underbalanced drilling

The pressure difference between the annular pressure and the formation pressure must always be maintained to get better results and for successful aerated drilling. A simulation of the calculation model was made to find the pressure profile of aerated drilling at the annulus and drillstring by using different air-water ratios. This profile was then compared with the formation pressure to obtain the differential pressure between annular pressure and formation pressure.

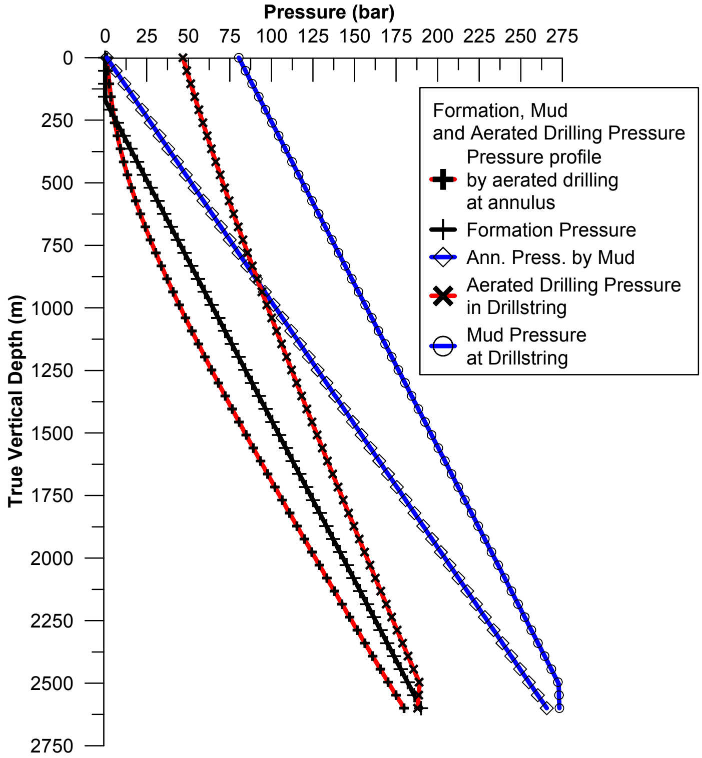

FIGURE 14: Pressure profile for aerated drilling fluid and mud inside annulus and inside drill string, and in the formation

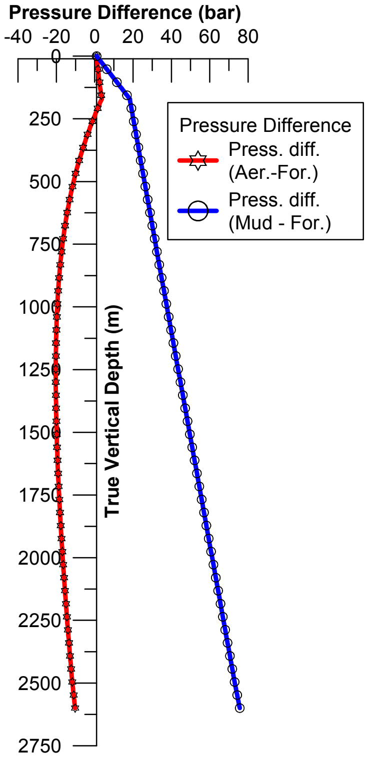

FIGURE 15: Pressure difference for aerated drilling fluids (annular pressure - formation pressure)

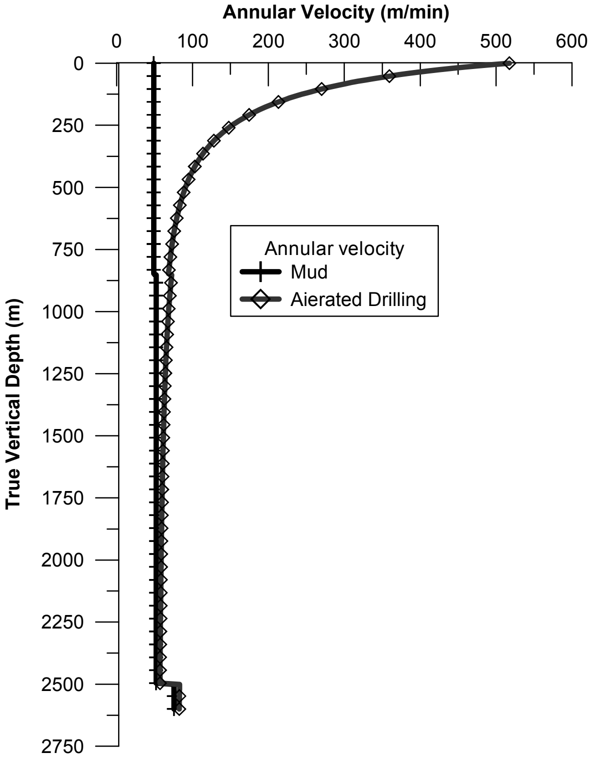

FIGURE 16: Different velocities between mud and aerated drilling

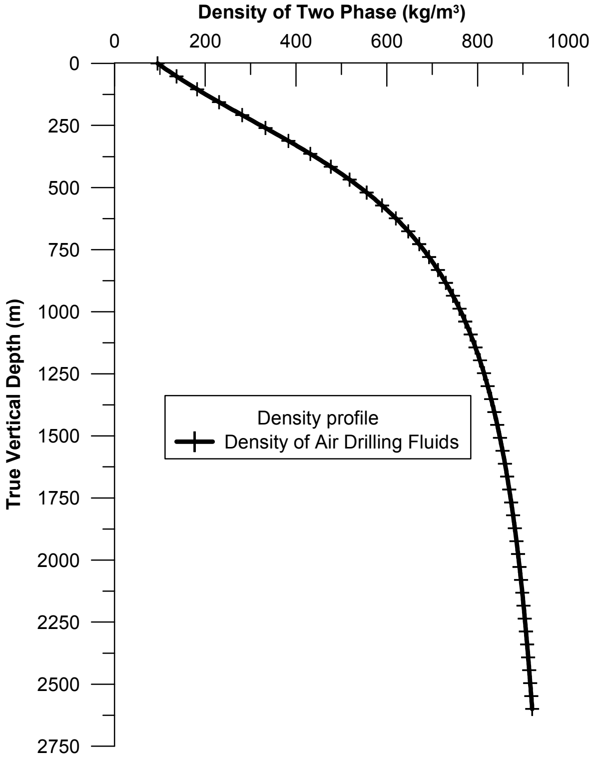

FIGURE 17: Density of aerated drilling fluids as a function of depth

The casing design for the calculation was the same as above. The inputs for aerated drilling that were assumed in this model are the following:

- Flow rate of water is 55 l/s;
- Backpressure at flowline is 1.5 bar;
- The circulation temperature is from the STAR model;
- Air-water ratios are assumed 1.37%, 1.63% and 1.78% (1300, 1550 and 1700 scfm).

Changing the ratio of air to water in the drilling fluid will change the annular pressure at the bottom hole of the hole. A higher air-water ratio in aerated drilling means less density of aerated drilling fluids, thus less annular pressure. Figure 18 shows the different profiles for annular pressure and pressure inside the drillstring for the different air-water ratios in the aerated drilling fluid, while Figure 19 shows more details through the differences in pressure (annular pressure – formation pressure). Thus, from the calculation model, we can conclude that the annular pressure can be maintained in an underbalanced condition and the pressure difference minimized by the changing air-water ratio.

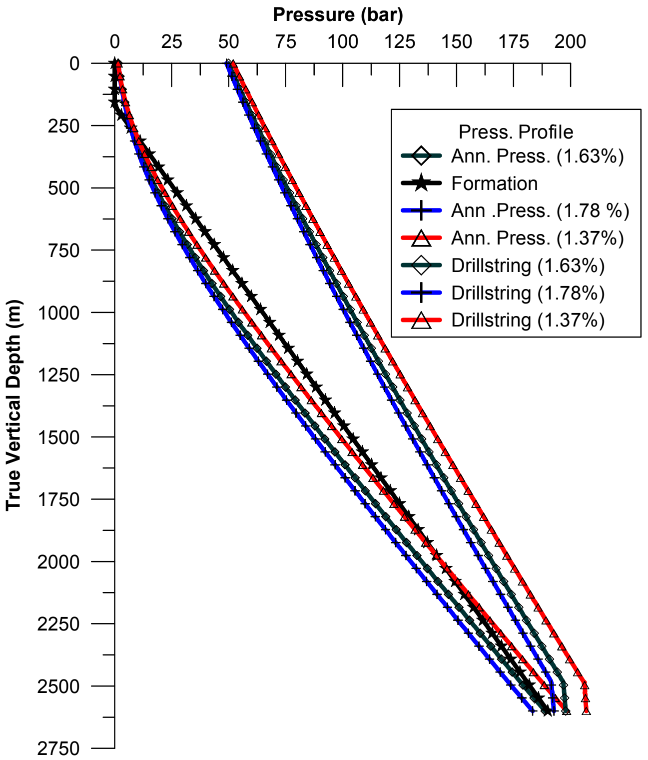

FIGURE 18: Impact to pressure profiles at annulus and drill string through using different ratios of air-water

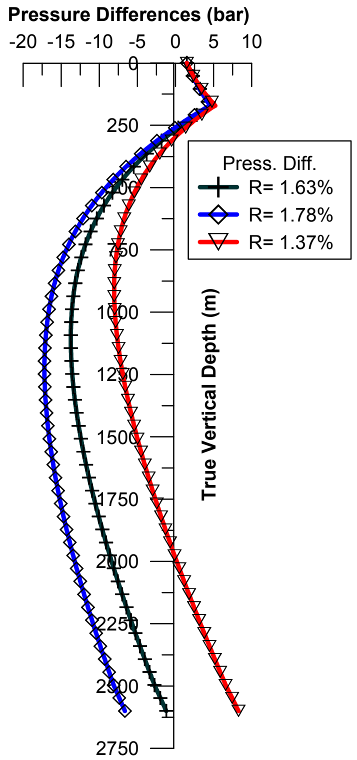

FIGURE 19: Pressure difference when using different rations of air-water in the drilling fluid (annular pressure - formation pressure)

Another simulation with the calculation model was made to find the pressure profile by aerated drilling at annulus and drillstring through changing the back pressure at the flowline. This annular pressure profile was then compared with the formation pressure to obtain the differential pressure.

The casing design for the calculation was the same as before and the inputs for aerated drilling that were assumed in this model are:

- Flow rate of water is 55 l/s;
- Backpressure at flowline is 1 bar, 1.5 bar and 3 bar;

- Circulation temperature is from STAR model (input 10°C, output 22.51°C);
- Air-water ratio is 1550 scfm (1.63%).

Figures 20 and 21 show the results of applying different backpressure at the flow line by adjusting the choke valve, they show that if higher backpressure is applied at the flowline the annular pressure increases at the bottom of the hole and in the drill string. Figure 20 shows the changes of the pressure profile in the annulus and inside the drill string with different back pressure settings, while Figure 21 shows more details through the differential pressure (annular pressure – formation pressure) at depth.

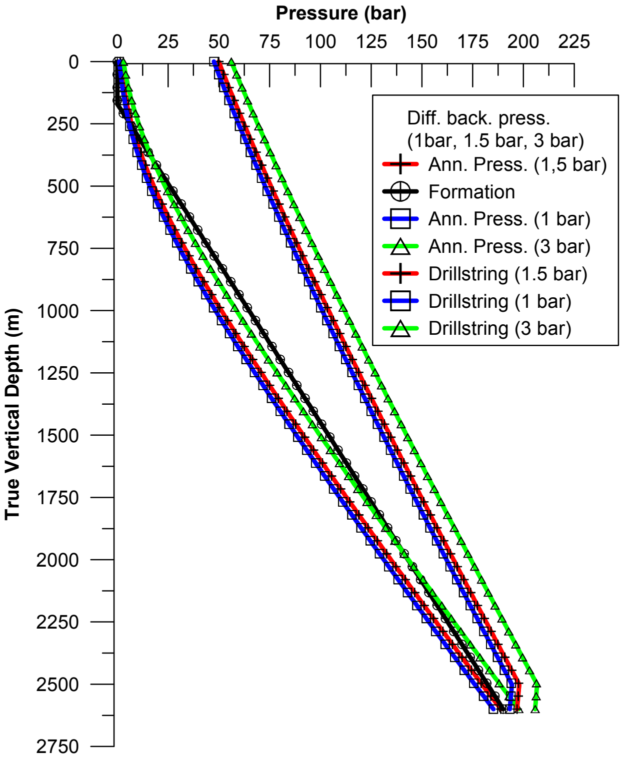

FIGURE 20: Impact of applying different backpressure at flow line to the pressure profile at annulus and drill string

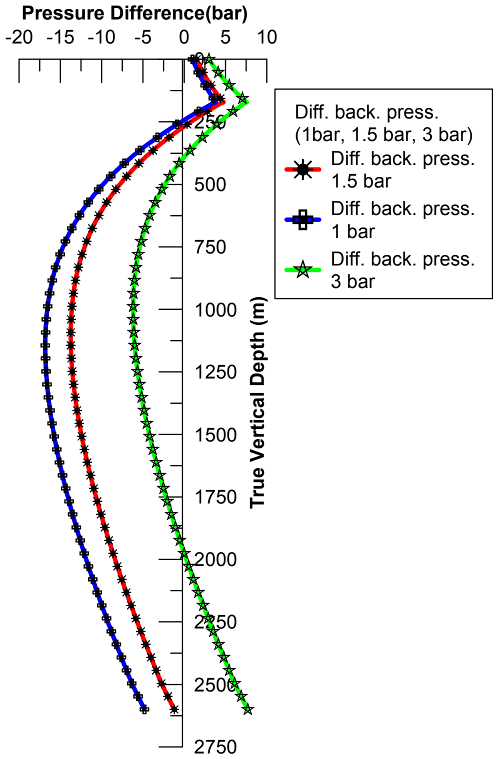

FIGURE 21: Pressure difference when applying different backpressure (annular pressure - formation pressure)

Figures 20 and 21 show that by adjusting the backpressure, the whole pressure profile can be shifted to a desirable position. The density response to the back pressure is much more rapid than changing the air-water ratio. However, successful under-balance or balanced drilling operations always require the supervision of a qualified operator, as adjustments have to be made on the go. The calculation procedures described here can aid in planning such aerated drilling operations and serve as a guide for the supervisor.

4. CASE STUDIES OF DRILLED WELLS

This chapter reviews drilling of wells LHD-23 and UBL-3 in Indonesia and makes some comparison with well HE-45 in Iceland. It focuses on the drilling of the production part of the wells (after production casing), and borehole problems that are possibly caused by drilling fluids.

Well LHD-23:
It is located in the Lahendong geothermal field in Sulawesi, Indonesia. Drilling of the well was done with rig N-80 UE, starting on 30 December 2005 and finishing on 19 March 2006 (lasting in all 80 days). The well is a directional well with a kick off point at 250 m, and with an inclination of 47°. The casing design is the following:

- Shoe for 20" casing is at 205 m;
- Shoe for the 13⅜" casing is at 831.5 m, the float collar at 819.39 m and DSCC at 204.52 m;
- Shoe for the 9⅝" casing is at 1704 m with top liner hanger from 1701.68 m. The 9⅝" casing (slotted liner) was set in the interval 810.24-1704 m;
- The 7" casing (slotted liner) was set in the interval 1703.48-2000 m.

Mud was used as the drilling fluid in well LHD-23. During drilling with the 12¼" bit, a loss of circulation occurred starting at 1372 m depth. Partial loss of circulation 40-60 litre per minute (l/min.) continues in the interval 1372-1580 m. The partial loss of circulation increased from 1580 m and was then followed by a total loss of circulation, 3500 l/min. from 1703 to 2000 m. The pump pressure was 0 psi (0 bar) from 1813 to 2000 m. Blind drilling (only using water as the drilling fluid) was done from 1704 m because mud mixing could not follow the volume of circulation loss. The flow rate of drilling fluids in the production zone was 2650-2953 l/min. with SG 1.03-1.06 (Silaban et al., 2006).

A single shot survey run in the borehole was carried out after the circulation was lost with dynamic losses of 130 l/min. and static loss of 6.5 l/min. The drill pipe got stuck after this survey with the bit at 1596 m. The time needed to release the pipe was 1 day (24 hours 30 minutes) by jarring up and down and using mill free. The drill pipe got stuck again during blind drilling with water and a jointed drill pipe at 1804 m. Here, the time needed to release the pipe was 1 hour 30 minutes by jarring 63 times.

UBL-3
UBL-3 is an exploration well located in the Ulubelu geothermal field in Indonesia which is owned by PT. Pertamina Geothermal Energy. It has the coordinates X= 451.956, Y = 9.413.481 and Z = 851 m. UBL-3 was drilled from 21 March 2008 to 9 May 2008 (or for 50 days). The depth was scheduled to be about 2500 m, but the final depth reached through drilling was 2320 m (measured depth) or 2224 m (true vertical depth). Drilling in the production zone was mainly done with aerated drilling fluids but sometimes without air and sometimes with high-viscosity drilling fluids. The actual casing programme was as follows:

- 30" stove pipe down to 30.7 m;
- 20" casing down to 303.14 m;
- 13⅜" casing down to 875.07 m;
- 9⅝" casing down to1870 m;
- Shoe liner for 7" slotted liner is at 2274.5 m;
- Top socket for 7" slotted liner is at 1800 m.

Borehole problems while drilling after putting in production casing included loss of circulation, flow and cuttings not carried to the surface. They are summarized here below (Supriyatna et al., 2008):

- During drilling from 1209 to 1228 m, 2,294 l/min. (606 gpm – gallons per minute) of water and 1500 scfm of air were flowing from the well (during circulation). Annular pressure increased 4.14 bar (60 psi) and the temperature was registered at 51°C. To solve this problem, water was pumped into the well at 3,217 l/min. (850 gpm) through the drill string and 795 l/min. (210 gpm) through the annulus.
- After drilling from 1247 to 1278 m with 2,294 l/min. (606 gpm) of water and 2000 scfm of air, there was flowing from the well (during circulation). This was identified by an annular pressure increase of 4.14 bar (60 Psi) and a temperature rise to 90°C. This problem was solved by

bypassing the pressure to ground pit 2 and pumping water to the well, 1,514 l/min. (400 gpm) through annulus and 3,218 l/min. (850 gpm) through the drill string at a casing pressure of 2.76 bar (40 psi) and area drill string. The pipe became stuck at 1278 m, but through over pull of 40-50 tons, and pushing drill string with 100 tons two times, the drill string became unstuck.

- After drilling from 1414 to 1451 m with 2,495 l/min. (659 gpm) of water and 1,500 scfm of air, there was still flowing from the well (while loading with 1,600-2,500 scfm of air). This flow was deduced by an annular pressure increase of 5.52 bar (80 psi) while the temperature became 93°C. To solve this problem, water was pumped into the well: 3,785 l/min. (1,000 gpm) through the drill string and 909 l/min. (240 gpm) through the annulus.
- After drilling from 1537 to 1539 m with 2,461 l/min. (650 gpm) of water and 1600 scfm of air, there was flowing from the well, deduced by an annular pressure increase of 6.89 bar (100 psi) and a temperature of 47°C. To solve this problem, water was pumped into the well at the rate 3,217 l/min. (850 gpm) through the drill string and 1,514 l/min. (400 gpm) through the annulus.
- After pulling out the 12¼" borehole bit used from 1568 to 1583 m, flowing began again. To stop this flow from the well, water was pumped through the annulus at the rate 1,491 l/min. (394 gpm) and through the drill string at 2,919 l/min. (771 gpm).
- After reaming and wash down from 1566 to 1583 m with 2,317 l/min. (612 gpm) of water and 1,200 scfm of air, flow began. To stop this flow, water was pumped through the annulus at 1,514 l/min. (400 gpm).
- After drilling from 1583 to 1585 m with 2,495 l/min. (659 gpm) of water and 1,000 scfm of air, there was flowing from the well, identified by an annular pressure increase of 2.76 bar (40 psi) and temperature of 45°C. To solve this problem, water was pumped into the well at the rate 2,033 l/min. (537 gpm) through the drill string and 1,461 l/min. (386 gpm) through the annulus.

Near the final depth of UBL-3, the following has been taken from the daily report:

- Drilling through formation from 2163 to 2107 m, rig pump is at 1,741 l/min. (460 gpm) for drill string + 1,703 l/min. (450 gpm) for annulus + 1,600 scfm air.
- Drilling continued from 2107 to 2145 m, rig pump at 1,741 l/min. (460 gpm) - drill string + 1,703 l/min. (450 gpm) - annulus + 1,600 scfm air, no return of circulation. The flowing casing pressure was 6.89 bar (100 psi) and temperature 40°C, bypass to ground pit, killing of well with 1,514 l/min. (400 gpm) - drill string + 1,893 l/min. (500 gpm) – annulus.
- Continued drilling from 2145 to 2164 m, rig pump at 1,514 l/min. (400 gpm) for drill string + 1,893 l/min. (500 gpm) for annulus + 1,600 scfm air, no return of circulation.
- Continued drilling from 2164 to 2179 m, rig pump at 1,703 l/min. (450 gpm) for drill string + 1,700 scfm air, drilling stopped, drill string pulled to casing shoe, maintenance of air drilling.
- Run in with 8½" bit from casing shoe to 2126 m where it sits.
- Wash down and reaming to 2176 m, drilling to 2274 m, rig pump at 1,703 l/min. (450 gpm) + 1,600 scfm air, well flowing with casing pressure at 6.14 bar (89 psi) and temperature at 38°C.
- Drill formation from 2274 to 2320 m with 1,590 l/min. (420 gpm) + 1,600 scfm, sticking, 14 hours needed to get unstuck by pulling and pushing the drillstring, pull load 125 tons and push load 50 tons and trying to rotate. After getting loose circulation was activated, and trying to wash down and ream well, sticking occurred again at 2286 m. Sweep with high-viscosity pill 30 bbls (4,770 l), released the sticking. After cleaning of the well, the decision was made to discontinue drilling. The 7" liner shoe was put at 2274.5 m

Figure 22 shows a comparison of the drilling time and operations for well LHD-23, which used mud as a drilling fluid, with wells UBL-3 and HE-45, both of which used aerated drilling fluids. From the figure it can be seen that the drilling progress of LHD-23 took the longest time because of a lower rate of penetration, but also due to some problems while drilling. The drilling problems in LHD-23 mainly related to a total loss of circulation, caused by annular pressure higher than the formation pressure. Nothing can be done to reduce the annular pressure. Even during blind drilling using water, the annular pressure was still higher. Cuttings were not delivered to the surface, with some of it carried to the formation while some of it remained in the hole, causing pipe sticking.

Air drilling was used in well UBL-3 as well as in HE-45, but UBL-3 took longer to drill. Drilling operations in HE-45 did not have problems such as flowing or pipe sticking, and cuttings were cleaned well in the drilling operation. The flowing during the UBL-3 drilling was probably caused by the annular pressure being lower than formation pressure, and the difference of annular and formation pressure being too high. During the drilling operation of UBL-3, circulation loss was sometimes found which means that the annular pressure was higher than the formation pressure.

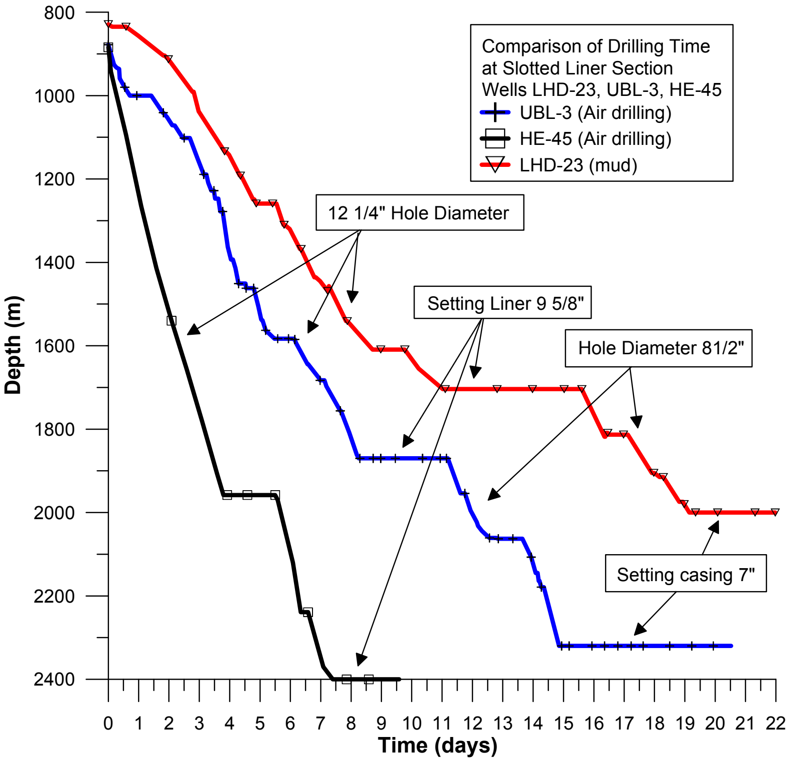

FIGURE 22: Comparison of drilling time for wells LHD-23 (mud), UBL-3 (aerated drilling fluid) and HE-45 (aerated drilling fluid)

The casing design of HE-45 was different from wells LHD-23 and UBL-3. The slotted liners in HE-45 are all with a diameter of 9⅝”, while in LHD-23 and UBL-3 the 9⅝” slotted liner was combined with a 7” slotted liner. The reason was that many pipes got stuck.

5. CONCLUSIONS AND RECOMMENDATIONS

Conclusions obtained from the simulated calculation model and analysis in the case study, include:

- Wells drilled with aerated drilling have, in several areas, been shown to have higher productivity than wells drilled with mud or water.
- Air drilling in geothermal fields is better than conventional drilling fluids because of its lighter density to combat loss of circulation due to low formation pressure which usually causes problems in drilling operation such as pipe sticking (caused by poor cleaning of the cuttings).
- Minimizing the difference between annular and formation pressures is important to reduce the possibility of borehole problems.
- As air drilling does not rely on chemicals that may possibly produce some kind of mud cake and minimizes loss of drilling fluids and cuttings to the formation, it reduces formation damage and improves the well production.
- The air drilling technique is also more flexible in maintaining the annular pressure by changing the ratio of air-fluids or by applying different back pressures at the flow lines.
- Reducing borehole problems means faster drilling progress. Faster rates of penetration (ROP) are also observed when drilling balanced or underbalanced.

Recommendations include the following:

- The annular pressure by air drilling must be maintained and regulated to reduce borehole problems by keeping it in under-balanced conditions (to reduce the possibility of circulation loss) and to minimize the pressure difference with the formation pressure (controllable flowing).
- Air drilling is best used during drilling of the production part of a well, after the production casing has been cemented in order to avoid loss of circulation to the production zone.
- More research needs to be done on the ability of lifting cuttings when using air drilling.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to Dr. Ingvar B. Fridleifsson, Director, and Mr. Lúdvík S. Georgsson, Deputy Director, for giving me the opportunity to attend the UNU Geothermal Training Programme in 2007. Furthermore, thanks go to Ms. Thórhildur Ísberg, Ms. Dorthe Holm and Mr. Markus A.G. Wilde for their help during the course. My sincere thanks to my supervisor, Mr. Sverrir Thórhallsson for guidance and advice throughout the project and to Mr. Peter Eric Danielsen and Ms. Christa for helping me in data collection for my project. Special thanks to all the lecturers for their comprehensive presentations and willingness to share their knowledge and experience.

I would also like to give thanks to the management of PT. Pertamina Geothermal Energy for permission to attend this programme. Finally, my deepest thanks go to my family, the UNU Fellows of 2008 and friends for their moral and emotional support during these six months.

REFERENCES

Binder, J., 2007: New technology drilling rig. *Proceedings of the European Geothermal Congress 2007, 4 pp.*

Bjelm, L., 2006: Underbalanced drilling and possible well bore damage in low-temperature geothermal environment. *Proceedings of the 31st Workshop on Geothermal Reservoir Engineering, Stanford, Ca,* 6 pp.

Gabolde G., and Nguyen, J.P., 1991: *Drilling data handbook*. Gulf Publishing Co., Houston, TX, 542 pp.

Hole, H., 2006: *Lectures on geothermal drilling and direct uses.* UNU-GTP, Iceland, report 3, 32 pp.

Huang Hefu, 2000: Study on deep geothermal drilling into a supercritical zone in Iceland. Report 7 in: *Geothermal training in Iceland 2000.* UNU-GTP, Iceland, 105-137.

Nur, S., Dody, N., and Rejeki, H.S., 2005: Laboratory study of high temperature additives to rheology of drilling mud under dynamic conditions. *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey,* CD, 7 pp.

Perez-Tellez, C., 2003: *Improved bottomhole pressure control for underbalanced drilling operations.* Louisiana State University, Dept of Petrol. Engineering, PhD thesis, 164 pp.

Russel, M.A.C., 1987: The use of aerated fluids in geothermal drilling. *Proceedings of 9th New Zealand Geothermal Workshop, Auckland University, NZ,* 153-157.

Silaban, M., Yani, A., Tesha, Kustono, H., Budi, I.M., and Nugroho, A.J., 2006: *Drilling report LHD-23*. PT. Pertamina Geothermal Energy, Indonesia, internal report.

Supriyatna, A., Huntoro, T., Tedy, S. and Priyo, S., 2008: *Daily report UBL-3.* PT. Pertamina Geothermal Energy, Indonesia, internal report.

Thórhallsson, S., 2008: *Geothermal drilling technology.* UNU-GTP, Iceland, unpubl. lecture notes.

Zwager, D., 2007: *Airbased drilling technique for faster and easier drilling process and maximizing production from geothermal wells* (in Indonesian). PT Air Drilling, Indonesia, brochure.