

## DRILLING FLUIDS FOR DRILLING OF GEOTHERMAL WELLS

Hagen Hole  
Geothermal Consultants NZ Ltd., Birkenhead, Auckland, New Zealand.

### ABSTRACT

Drilling fluids are required to remove cuttings from the well during drilling, to cool and lubricate the drill bit and drill string, to apply pressure to formation fluids to control flow into or out of the well, and to cool the formation, particularly prior to cementing casings. Various drilling fluids are selected according to reservoir pressures and temperatures and to the drilling techniques to be utilised. Drilling fluids normally used include water, water based bentonitic (or other) muds, aerated water, and stiff foam.

Because many geothermal reservoirs are set in interlayered volcanic and sedimentary rock and are normally associated with local and regional faulting, highly permeable features are common and cause major and frequent losses of drilling fluid circulation.

The utilisation of aerated fluids and the concept of 'balanced' downhole pressure conditions allows for full circulation of drilling fluids and drilling cuttings back to the surface while drilling through permeable formations, thus significantly reducing the risk of the drill string becoming stuck, of formation and wellbore skin damage, and for full geological control.

*Keywords: geothermal, drilling fluids, aerated drilling*

### INTRODUCTION

The circulation of 'drilling fluid' is an integral part of rotary and percussion drilling, and depending on the fluid type can fulfil all or some of the following functions:-

- Removes cuttings from the bottom of the hole – at the bit face.
- Returns cuttings to the surface (circulating conditions).
- Holds cuttings in suspension when circulation is stopped.
- Releases cuttings from the drilling fluid at the surface.
- Cools and lubricates the drill bit.
- Lubricates the drill string.
- Cools the hole and prevent liquid in the well from boiling.
- Controls downhole pressure preventing the well from flowing.
- Carry weighting material to increase fluid density to prevent the well from flowing and possibly blowing out.

- Reduces losses of drilling fluid by forming an impermeable 'wall cake' or lining to the hole wall.
- Reduces the rate of breakdown of water sensitive formations.

These functions are those desirable in drilling fluids utilised in petroleum wells, some water wells, and in the upper parts of a geothermal well. However, not all of these properties are necessarily desirable in all sections of a geothermal well.

### DRILLING FLUID PROPERTIES

The primary function of a drilling fluid is to remove the drilling cuttings from the bottom of the hole and carry them to the surface.

#### ***Slip Velocity***

The ability of a drilling fluid to entrap and carry granular particles from the drill bit face to the surface is dependent upon the annular velocity of the drilling fluid exceeding the 'slip velocity' of the cuttings particles in that drilling fluid.

In the context of drilling, this 'slip velocity' may be described as the upwards annular drilling fluid velocity required to impose an upwards drag force on a cuttings particle equal to the downward gravitational force on that particle. If the upwards drag force does not exceed the downwards gravitational force the cuttings particle will not be lifted.

The drag force on a cuttings particle is dependent upon the size, shape and density (or wetted surface area and mass) of the particles, the viscosity of the fluid, and the upwards vertical velocity component of the fluid.

The size, shape and density of the particles being drilled are related to the rock type, the drill bit type and how well cuttings are being cleared away from the bit (and not being reground). The rock density, and the size and shape of the cuttings being produced are parameters which are not easily controlled or changed, however the drilling fluid viscosity and the drilling fluid flow rate and therefore annular flow velocity can be controlled within certain limits.

#### ***Fluid Viscosity and Flow Velocity***

Fluid viscosity and fluid flow velocity are inversely proportional with respect to 'Slip Velocity' of a particular particle – in other words, if the fluid viscosity is increased, a reduced fluid flow velocity will be required to maintain the same slip velocity for a particular particle.

However, there are practical limitations to the range of fluid viscosities and fluid annular velocities that can be utilised.

Higher viscosity drilling fluids impose higher drag forces upon entrained cuttings particles and therefore produce better hole cleaning – but, higher viscosity fluids also impose higher pressure losses and therefore require higher pumping pressures.

Higher annular velocities ensure the particle – fluid slip velocity is exceeded, but increase the risk of scouring unconsolidated formation from walls of the hole and also impose higher pressure losses and therefore require higher pumping pressures.

### ***Thixotropy and Gel Strength***

The ability of a drilling fluid to hold cuttings in suspension during periods of no circulation, and of releasing the cuttings from suspension at the surface require a special property – Thixotropy.

A Newtonian fluid such as water, oil, and glycerine, maintains a constant viscosity while stationary or while flowing – the fluid viscosity is independent of any applied sheers stress. The viscosities of Non-Newtonian fluids such as water based bentonite mud, some polymers and some cement slurries varies as a function of the applied sheer stress – this property is Thixotropy. When the fluid is stationary the fluid builds gel strength and the viscosity increases; if the fluid is pumped and forced to flow, the viscosity reduces.

This thixotropic property is ideal for holding cuttings in suspension during period of no circulation, and for releasing cuttings when the fluid is subjected to high cheer stress, such as passing over a linear motion shale shaker.

In addition to this process of holding cuttings in suspension and releasing them at the shale shaker, this thixotropic property also allows a layer of gelled fluid to build on the hole wall, creating a protective and somewhat impermeable lining or ‘wall cake’ on the hole wall.

### ***Water Based Bentonite Mud***

The most commonly used geothermal drilling fluid that exhibits the properties described above is water based bentonite mud, which typically comprises bentonite, water and caustic soda. Other chemicals may be added to control the physical properties of the fluid as required by the downhole conditions, and these will include:-

- Thinner to control viscosity and gel strengths
- Fluid loss control agents to control the loss of water from the mud which in turn controls excessive build-up of wall cake.
- Weighting materials such as barite to increase mud density (rare in geothermal)
- Loss of Circulation Materials (LCM) to aid in reducing the loss of drilling fluid to the formation.

- Corrosion control additives may also be added to the mud.

The solid content of the mud is derived from bentonite, non-clay materials contained in the bentonite, weighting materials if utilised, and drilled cuttings particles which may include sand and clay minerals. Solids other than bentonite or weighting materials generally have adverse effects on the drilling operations. Increased mud density can reduce penetration rates and cause circulation losses. Sands can increase wear on pumping equipment and downhole tools (stabilisers, reamers, bits), drill string and casing. Drilled clays can cause excessive viscosity build-up and, together with other drilled solids, can build up thick wall cakes in the hole and around stabilisers. It is therefore desirable to remove as many of the drilled solids from the drilling fluid as is possible.

As drilling proceeds and the formation temperatures increase with depth, the drilling fluid is inevitably heated. At elevated temperatures the gelling properties and viscosity of bentonite muds increase, and the mud begins to flocculate. Dispersant and deflocculating additives, and cooling the circulating fluid can assist in controlling this problem.

Over the past 10 years polymeric fluids have been developed and introduced into the drilling industry. Synthetic drilling polymers exhibit many of the same properties as water based bentonite and are now being utilised more frequently in geothermal drilling – however, polymeric drilling fluids are extremely expensive and are therefore used sparingly.

### ***UNDERBALANCE AND OVERBALANCE***

In a typical ‘under-pressured’ geothermal system, the pressure of the drilling fluid in the well exceeds the pressure of the fluids in the formation at the same depth. This is an “overbalanced” condition – the opposite condition or “underbalanced” conditions may occur when a total loss of circulation allows the liquid level in the annulus to move down the well, or when intentionally established using aerated drilling methods. Drilling in an underbalanced condition encourages inflow of formation fluids (gas, steam or hot water) and sloughing of formations. Unless controlled, licks and stuck drill string can result. However, drilling with excessive overbalanced pressures can cause slow penetration rates, high loss of mud filtrate resulting in thick soft wall cake development and breakdown of the formation and subsequent loss of circulation.

Where conditions of a large overbalance pressure and a thick soft wall cake are present adjacent to the drill string (particularly non-stabilised and slick drill collars), the drilling tubulars can be forced into the wall cake by the overbalance pressure and cause the drill string to become securely stuck in the wall cake. This action, referred to as “differential sticking”, is a frequent cause of stuck drill strings and is best avoided

by using mud weights which give minimum water loss (to reduce the build up of wall cake) and low inactive solids content (to reduce the strength of the wall cake).

## LOSS OF CIRCULATION

The common denominator of all convective hydrothermal systems – the majority of all developed geothermal fields, is the highly permeable, fractured and faulted nature of the formations in which the geothermal reservoirs reside. This high permeability being one of the fundamental and requisite components for any geothermal system to exist.

Typically, the permeable nature of the formations is not limited to the geothermal reservoir structure alone, but often occurs in much of the shallower and overlying formations as well. This, coupled with the under-pressured nature of most geothermal systems, results in the partial or total loss of circulation of drilling fluid at some stage during the drilling of the well - in fact ultimately if circulation is not lost in an under-pressured system this is an indication that there is no permeability and therefore the well a 'dry well'.

The thixotropic and gelling nature of water based bentonite mud assists in the sealing of minor loss zones, and with the addition of loss circulation materials (LCM) many minor loss zones can be completely sealed. However, if major or total losses of circulation are encountered, and can't be sealed with LCM added to the mud, then it becomes impractical and uneconomic to continue drilling with mud. If high permeability and therefore significant or total losses of circulation are encountered within the upper cased sections of the well the use of water based bentonite mud and additives is normally ceased, and drilling is continued with water or with aerated water.

When drilling the production section of the well within the reservoir structure, the elevated temperatures and the targeted permeability render the properties of bentonite muds undesirable. The drilling of a geothermal well has as it's primary objective, drilling into, and preserving permeable formations within the reservoir structure, which will, after completion of drilling become the production zone of the well.

If bentonite mud is forced into the permeable structure of the reservoir, the gelling and sealing properties can cause permanent damage to the productivity of the zone. The high temperatures dehydrates and bakes the bentonite clay into a relatively inert and impermeable material. A process similar to baking clay into pottery.

It is therefore usual and accepted practice that this section of the well is drilled with water or aerated water.

## DRILLING WITH WATER

Water as a drilling fluid was, in the past, used to continue drilling past an unsealable loss zone and for the final production section of a geothermal well. When drilling into a permeable 'under pressured' zones the drilling fluid circulation is lost, and the drilling

fluid flows into the formation rather than returning to the surface.

The traditional method of dealing with this situation was to continue drilling 'blind' with water – the pumped water being totally lost to the formation with the drilling cuttings being washed into the formation as well. The major problem with this method of drilling is that the cuttings rarely totally disappear into the formation. Stuck drill string due to a build up of cuttings in the hole, and well-bore skin damage being common occurrences.

The advantages using water as drilling fluid are:-

- As the water is not recirculated but is lost to the formation, the downhole temperature significantly lower, extending drill bit life and reducing the likelihood of a kick developing.
- As lower bottom hole circulating pressures are developed, penetration rates are higher.
- Because mud and thick wall cake are not squeezed into permeable zones, reduced formation sealing and increased well productivity are achieved.
- Because a wall cake is not developed, differential sticking does not occur. Where a wall cake is present from earlier drilling, the lower downhole circulating pressures significantly reduces or eliminates the risk of differential sticking.

The disadvantages of using water as drilling fluid are:-

- A continuous large volume (~3500 lpm) supply of water to the drilling rig is required.
- As water has a low viscosity, is not thixotropic and cannot develop gel strength, slip velocities are higher requiring increased annular fluid velocities, and as soon as pumping to the drill string is stopped (e.g. to make a connection), any cuttings suspended in the annulus will start settling immediately, which increases the risk of stuck drill string.
- Cuttings are not returned to the surface, but washed into the permeable zones.
- No geological data, as no return of cuttings to the surface.
- The loss of cuttings into the permeable zones may reduce permeability (not as much as mud).
- When pumping is stopped cuttings accumulated in permeable zones may flow back into the well increasing the risk of stuck drill string.
- Loss of large volumes of cold water to the formation can cause long recovery periods after drilling is completed before the well can be discharged.

Great care must be exercised when drilling with water to avoid becoming stuck with cuttings settling down the annulus.

## AERATED DRILLING

'Aerated Drilling' may be defined as the addition of compressed air to the drilling fluid circulating system to reduce the density of the fluid column in the wellbore annulus such that the hydrodynamic pressure within the wellbore annulus is 'balanced' with the formation pressure in the permeable 'loss zones' of a geothermal well.

### Drilling Processes

The primary objective of utilising aerated drilling fluids is the ability to maintain drilling fluid circulation and therefore the clearance of cuttings from the hole as drilling proceeds into permeable and 'under pressured' zones.. This continuous clearance of cuttings from the hole significantly reduces the risk of the drill string getting stuck in the hole.

Aeration of the drilling fluid reduces the density of the fluid column and thus the hydraulic pressure exerted on the hole walls and the formation. As the introduced air is a compressible medium, the density of the column varies with depth – at the bottom of the hole where the hydrostatic pressure is greatest, the air component is highly compressed and therefore the density of the fluid is greatest; at the top of the hole, where the hydrostatic pressure is least, the air component is highly expanded and therefore the density of the fluid the least. The ratio of air to water pumped into the hole, and the back pressure applied to 'exhaust' or flowline from the well, allows the down-hole pressures in the hole to be 'balanced' with the formation pressure in the permeable zones, thus allowing for the return of the drilling fluids to the surface and therefore maintaining drilling fluid circulation. (In fact the term 'under-balanced' drilling as applied to this form of geothermal drilling is a misnomer).

Initially the technique was utilised only in the smaller diameter production hole section of a well, however, in some fields permeability is prevalent in the formations located above the production zone, and significant amounts of lost time can be incurred in attempting to plug and re-drill such zones. Utilising aerated fluids to drill these zones has proven to be a highly successful solution.

### Formation and The Resource

Perhaps the most important feature of aerated drilling is its effect on the productivity of the well. The removal of the drill cuttings from the well bore, rather than washing the cuttings into the permeable zones, reduces the potential of blocking up and in some cases sealing the permeability close to the wellbore – the effect called well-bore skin damage. A relatively small amount of interference to the flow from the formation into the well-bore, or skin damage, can have a significant effect on the productivity of the well.

Wells drilled with aerated fluids, and thus with full circulation and removal of drill cuttings show less skin damage than those drilled 'blind' with water.

In general terms, wells with the production zone drilled with aerated fluids demonstrate better productivity than those drilled blind with water, and significantly better productivity than those drilled with bentonite mud in the production zone.

A previous drilling campaign in Kenya allows for a direct comparison between a number wells drilled as immediate offsets, to similar depths in similar locations; the original set of wells were drilled blind with water (and in one case mud) and a more recent set drilled with aerated water. The productivity of the wells drilled with aerated fluids, on average is more than double that of the wells drilled without air.

Wells Drilled Blind with water		Wells 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
<b>Average</b>	<b>22.87 MWt</b>		<b>58.04 MWt</b>

Table 1: Comparison of Thermal Outputs of wells drilled with and without Aerated Fluids at Olkaria – Kenya.

### Cuttings Return

As indicated above, the primary objective of utilising aerated drilling fluids is the maintenance of drilling fluid circulation, the obvious corollary to this is the continued return of drilling cuttings back to the surface, and thus the ability to collect and analyse cuttings from the total drilled depth. While this is not always achieved for the entire drilled depth of wells drilled with aerated fluids, it is usual for circulation to be maintained for a significant proportion of the drilled depth.

### Drilling Materials

A significant reduction in the consumption of bentonite drilling mud and treating chemicals, cement plugging materials, and bentonite and polymer 'sweep' materials can result from the use aerated water or mud.

In addition a major reduction in the quantities of water consumed occurs. Typically, approximately 2000 litres per minute will be 'lost to the formation' while drilling an 8½" hole 'blind with water'. Aeration of the fluid allows almost complete circulation and re-use of drilling water.

### ***A Fishing Tool***

Perhaps the most common reason for stuck drill-string is inadequate hole cleaning – the failure to remove cuttings from the annulus between the hole and the drill string. Often, the hole wall in the region of the loss zone acts as a filter, allowing fine cutting particles to be washed into the formation while larger particles accumulate in the annulus. Under these circumstances, if a new loss zone is encountered and all of the drilling fluid flows out of the bottom of the hole, these accumulated cuttings fall down around the bottom hole assembly and can result in stuck and lost drill strings. Aerated drilling prevents the accumulation of cuttings in the annulus and allows for circulation to be maintained even when new loss zones are encountered. In the event that a significant loss zone is encountered and the pressure balance disrupted, circulation may be lost and in severe cases the drill string may become stuck; with adjustment of the air / water ratio it is usually possible to regain circulation, clear the annulus of cuttings and continue drilling with full returns of drill water cuttings to the surface.

The air compression equipment has on numerous occasions been utilised to pressurise the annulus around a stuck drill-string, such that the water level in the annulus is significantly depressed. If the pressure in the annulus is then suddenly released the water in the annulus surges back up the hole, often washing cuttings or caved material packed around the drill string up the hole and thus freeing the stuck drill string.

### ***Well Recovery***

Wells drilled ‘blind 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. Aeration of the drilling fluid limits the loss of fluids to the formation and the cooling of the reservoir around the well. The temperature recovery of wells drilled with aerated fluids is significantly faster. Typically a well drilled with water ‘blind’ can take from 2 weeks to 3 months for full thermal recovery. Wells drilled with aerated fluids tend to recover in periods of 2 days to 2 weeks.

### ***DISADVANTAGES***

Whilst the aerated drilling technique provides many benefits, it also introduces some negative aspects.

#### ***Cost***

The rental of aerated drilling equipment, the additional fuel consumed plus two operators imposes an additional operational daily cost against the well.

Typically this additional cost will be in the order of US\$150,000 to \$250,000 per well, or if we assume a typical geothermal cost of US\$3.5 million, the aerated drilling component of this cost will be in the order of ±6.0%.

### ***Non-Productive Time Activities***

Aerated drilling requires the utilisation of a number of non-return valves or ‘string floats’ to be placed in the drill string. Prior to any directional survey these floats must be removed from the drill string – this requirement imposes additional tripping time of approximately half an hour each time a survey is carried out.

However, when comparing ‘non-productive’ between aerated drilling and ‘blind’ drilling with water, the time lost when washing the hole to ensure cuttings are cleared when ‘blind’ drilling is comparable if not more than that lost retrieving float valves when aerated drilling.

### ***Potential Dangers***

Drilling with aerated fluids requires the drilling crew to deal with compressed air and with pressurised high temperature returned fluids at times, neither of which are a feature of ‘blind’ drilling with water. These factors are potentially dangerous to the drilling crew and require additional training, awareness and alertness. The author is not aware of any notifiable ‘Lost Time Injuries’ that have occurred as a direct result of using aerated drilling fluids since the technique was introduced in the early 1980’s.

While drilling within a geothermal reservoir system under aerated ‘balanced’ conditions, the potential for the well to ‘kick’ is significantly higher than if being drilled with large volumes of cold water being ‘lost’ to the formation. Well ‘kicks’ are a relatively common occurrence when drilling with aerated fluids, however the use of a throttle valve in the blowout line causes an increase in back-pressure when an increase in flow occurs, which tends to automatically control and subdue a ‘kick’. The author is not aware of any uncontrolled blow-outs of geothermal wells that have results from the use of aerated fluids.

### ***Drill Bit Life***

Aerated drilling prevents the loss of drilling fluid to the formation and thus reduces the cooling of the formation and near well bore formation fluids. The drill bits and bottom hole assemblies used are therefore exposed to higher temperature fluids especially when tripping in, reducing bearing and seal life, and thus the bit life.

This reduced life is however, usually a time dependant factor, which, when drilling some formations is compensated by significantly increased rates of penetration. For example – the current aerated drilling

operations in Iceland have seen average penetration rates of up to two time (2x) that previously achieved.

## THE PROCESS

As stated above, to maintain drilling fluid circulation while drilling permeable formations, the hydraulic (hydrostatic and hydrodynamic) pressure in the hole must be 'balanced' with the formation pressure. To balance the pressure in the hole with the formation pressure, the density of the fluid in the hole must be reduced. Figure 2. depicts some typical geothermal formation pressure regimes with respect to a cold hydrostatic column of water from the surface. A static water level of 400 metres has been assumed.

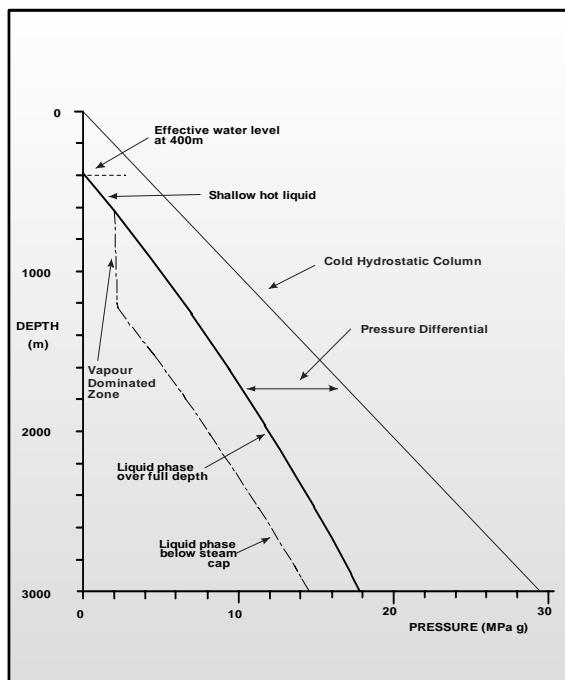


Figure. 2: Typical Formation Pressures

Figure 3. depicts typical pressures within a well with a range of drilling fluids with respect to a column of boiling water. The effective drilling fluid density can be varied in the approximate specific gravity range of 1.1 for un-aerated mud to 0.1 for air, by varying the ratio of air to liquid.

Fluid	Effective Specific Gravity
Water based bentonite Mud	1.1
Water	1.0
Oil Based muds	0.82
Aerated bentonite mud	0.4 – 1.1
Aerated water	0.3 – 1.0
Mist	0.05 – 0.4
Foam	0.05 - 0.25
Air	0.03 – 0.05

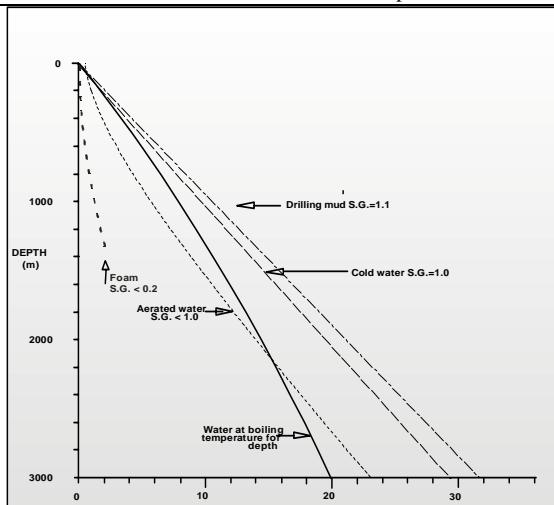


Figure 3. Typical Downhole Pressures

To 'balance' the downhole circulating fluid pressure with under-pressured formation conditions the density of the circulating fluid is reduced with the addition of air. The ratio of liquid to air, and the throttling of the circulating fluid outlet to produce a backpressure in the annulus are the variables which can be altered to provide the required pressure balance.

However, the addition of air into the drilling circulation system introduces a compressible component. The volume occupied by a unit mass of air at a particular depth in the hole is dependant on the fluid pressure at that depth. In other words the volume of a bubble of air at the bottom of the hole will be a small fraction of the volume occupied by the same bubble of air at the top of the hole. The density of the fluid column varies with depth and for simplicity purposes is described as a 'liquid volume fraction' (LVF).

A liquid volume fraction (LVF) of 1.0 = 100% liquid

A liquid volume fraction (LVF) of 0.0 - 100% air

So not only is the pressure regime within the hole altered, but circulating fluid volume, (the LVF) and therefore the fluid velocity varies with depth of the hole.

Table 2. indicates an output from the GENZL Aerated Drilling Computer Simulation Package, of a typical aerated downhole annular pressure profile with downhole pressure, differential pressure (the difference between the downhole pressure and the formation pressure with a nominal static water level at 300 m depth), the flow velocity, and the Liquid volume fraction (LVF) indicated as a function of depth.

The simulation is of a well with production casing set at 700 m depth, and a 100 m bottom hole drilling assembly (drill collars) – hence the parameter changes at these depths.

Meas. Depth (m)	Vert. Depth (m)	Annular Pressure (Barg)	Diff. Press. (Barg)	Velocity (m/min)	LVF
Blokie Line	0.0	1.9	1	742.0	0.10
100.0	100.0	4.6	3.6	219.6	0.21
200.0	200.0	7.9	6.9	148.7	0.31
300.0	300.0	12.0	11.0	113.9	0.40
400.0	400.0	17.0	7.4	94.5	0.49
500.0	500.0	22.6	4.4	82.7	0.56
600.0	600.0	28.9	2.3	75.0	0.61
700.0	700.0	35.6	0.9	69.7	0.66
700.0	700.0	35.6	0.9	78.9	0.66
800.0	800.0	42.9	-0.1	74.6	0.70
900.0	900.0	50.4	-0.4	71.4	0.73
900.0	900.0	50.4	-0.4	101.7	0.73
1000.0	1000.0	58.7	0.0	98.0	0.76
Bottom Hole	1000.0	58.7	0.0	98.0	0.76

Table 2. Simulation of Aerated Downhole Conditions

Plots of the various parameters are indicated in Figures 4, 5, 6, and 7.

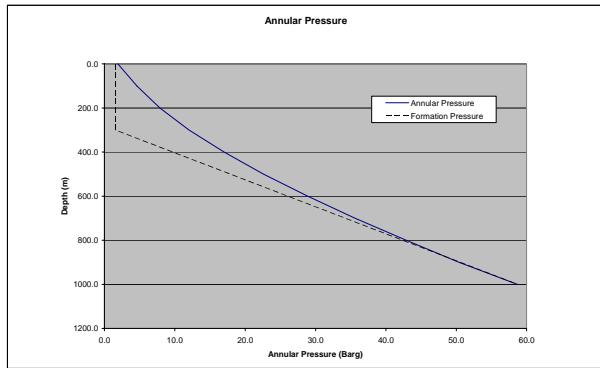


Figure 4. Annular Pressure and Formation Pressure V's Depth.

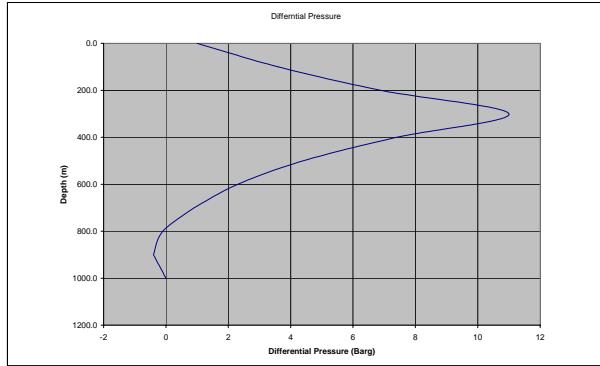


Figure 5. Differential Pressure V's Depth

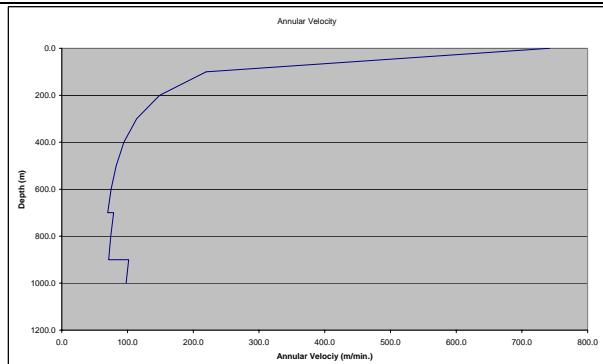


Figure 6. Annular Velocity V's Depth

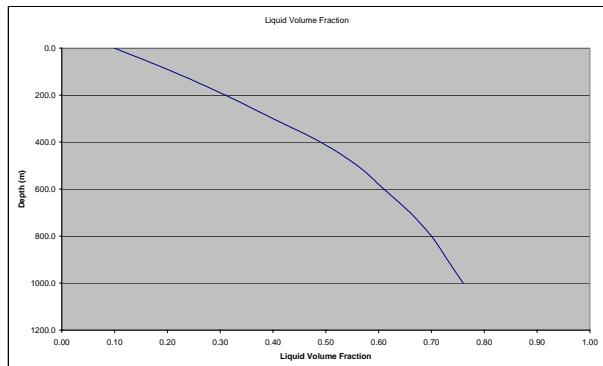


Figure 7. Liquid Volume Fraction V's depth

Perhaps the most critical point displayed by this data is that the fluid velocities around the drill bit and bottom hole assembly are very similar to the velocities that would occur without the addition of air. The volume of liquid to be pumped must be sufficient to provide lift to cuttings over the top of the bottom hole assembly, where the diameter of the drill string reduces from the drill collar diameter to the heavy weight drill pipe or drill pipe. Typically for water drilling, a minimum velocity of 45 to 55 metres per minute is required. The volume of air to be added to this liquid flow rate will be that required to reduce the density sufficiently to provide a balance, or a differential pressure of close to zero (0) at the permeable zone or zones.

## ACKNOWLEDGEMENTS

Thanks are given to Mr. Lindsay Fooks, Geothermal Associates New Zealand Limited for his major efforts and inputs into developing and upgrading this component of Geothermal well drilling.

---

## REFERENCES

Hole, H.M, 1992. "The Use of Aerated Fluids for the Drilling of Geothermal Wells" Lecture notes, Geothermal Institute, University of Auckland, New Zealand.

Hole, H.M., 1996. "Seminar on geothermal Drilling Engineering – March 1996, Jakarta, Indonesia", Seminar Text, Geothermal Energy New Zealand Limited, Auckland, New Zealand.

International Association of Drilling Contractors, 2003. "Underbalanced Drilling Operations – HSE Planning Guidelines", International Association of Drilling Contractors, Houston Texas, USA.

Gabolde, G., Nguyen, J.P, 1999. "Drilling Data Handbook – Seventh Edition". Institut Francais du Pétrole Publications.

NZS 2403:1991, "Code of Practice for Deep Geothermal Wells" Standards Association of New Zealand.