

## Aerated Fluids for Drilling of Geothermal Wells

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### ABSTRACT

The utilisation of aerated fluids for drilling geothermal wells 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.

The technique, an adaptation of straight air drilling and foam drilling techniques utilised by the oil and geothermal drilling industries, was initially developed by a team from Geothermal Energy New Zealand Ltd. during the late 1970's and early 1980's.

Since the initial development, the technique has been successfully utilised in many geothermal drilling programmes worldwide. Most recently, the technique was introduced into Iceland's geothermal drilling operations with remarkably successful results. To date 12 wells in three separate fields, Trolladygja, Hellisheidi, and Reykjanes have been completed successfully utilising aerated fluids.

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*Keywords:* geothermal, drilling, aerated drilling

### 1. INTRODUCTION

'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.

### 2. HISTORY

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 1970's, 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; and during the later part of this period GENZL developed its DOS based Air Drilling Simulation Package.

Subsequent aerated geothermal drilling operations occurred at the following geothermal fields as listed below:-

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.
- Salak - Indonesia
- Ohaaki, Mokai, Rotokawa, Putauaki, Wairakei, and Tauhara – New Zealand
- Trölladygja – Iceland
- Hellisheidi – Iceland
- Reykjanes - Iceland

### 3. BENEFITS

#### 3.1 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. This continuous clearance of cuttings from the hole significantly reduces the risk of the drill string getting stuck in the hole.

The majority of geothermal reservoir systems exist with a formation/system pressure which is significantly less than a hydrostatic column of water at any given depth within that system - in other words the reservoir systems are 'under-pressured'. When drilling into a permeable zone in such an 'under pressured' system, drilling fluid circulation is lost – 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.

A solution to these problems lies in the utilisation of reduced density drilling fluids.

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.

### 3.2 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 drilling campaign carried out in Kenya in the early 2000's 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.

### 3.3 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.

### 3.4 Enhanced Penetration Rate

The reduced bottom hole hydrostatic pressure imposed by aerated fluids results in enhanced rates of penetration in some formations. Penetration rates experienced in the basaltic lavas encountered in the Icelandic geothermal fields, have been as much as three times the penetration rates experienced in the same formations drilled conventionally.

### 3.5 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.

### 3.6 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.

### 3.7 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.

## 4. DISADVANTAGES

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

### 4.1 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%.

However, while the daily operating costs are higher, the overall well cost is normally reduced due to fewer drilling problems and higher penetration rates.

### 4.2 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.

### 4.3 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 blow-off 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.

### 4.4 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.

## 5. THE PROCESS

As stated in the Introduction 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. Typically geothermal systems are significantly 'under-pressured' with respect to a hydrostatic column of water to the surface. To balance the pressure in the hole with the formation pressure, the density of the fluid in the hole must be reduced. Figure 1. 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.

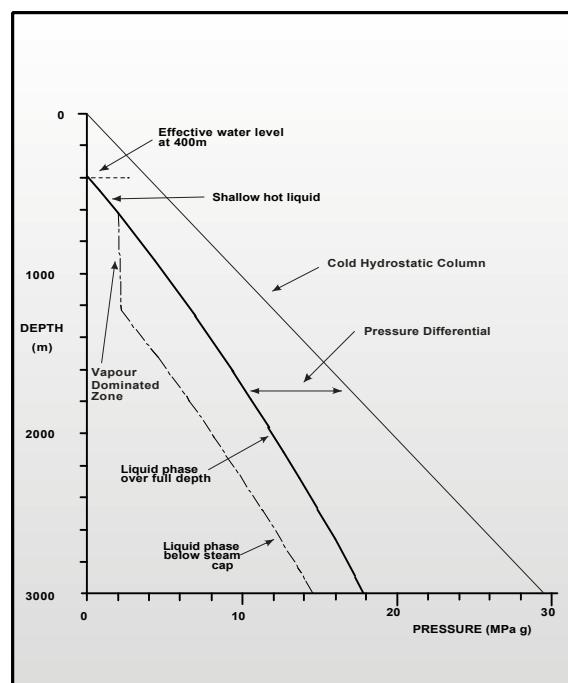


Figure. 1: Typical Formation Pressures

The primary objective of drilling a geothermal well is to encounter permeability, and therefore productivity (or injectivity); and because in most geothermal systems permeability is not limited to just the reservoir formations but is also prevalent in overlying formations. It is therefore inevitable that communication between the 'formation' and the fluid in the hole will occur.

Figure 2. 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

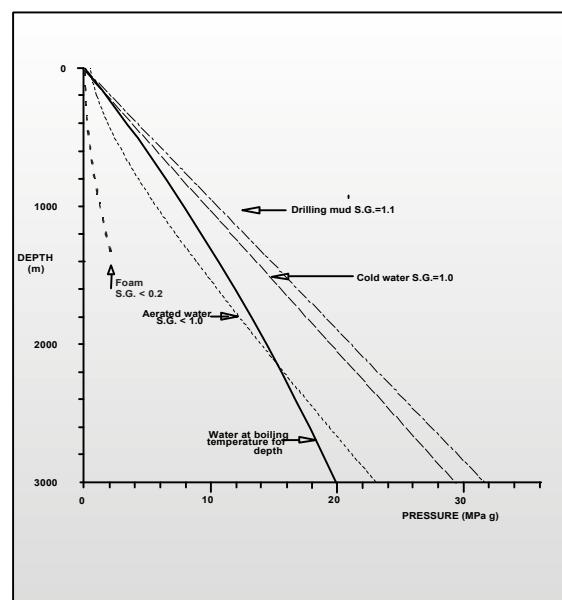


Figure 2. Typical Downhole Pressures

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).

LVF  
1.0 - 100% liquid  
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
Blooe 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.

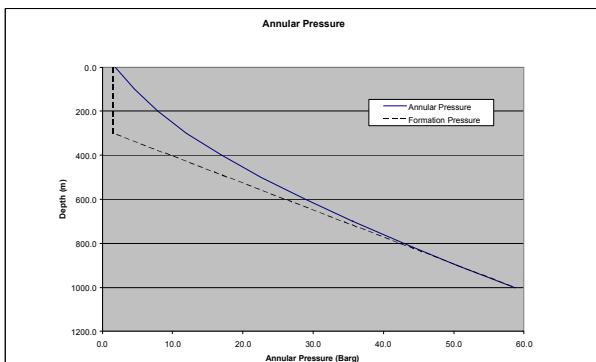


Figure 4. Annular Pressure and Formation Pressure V's Depth.

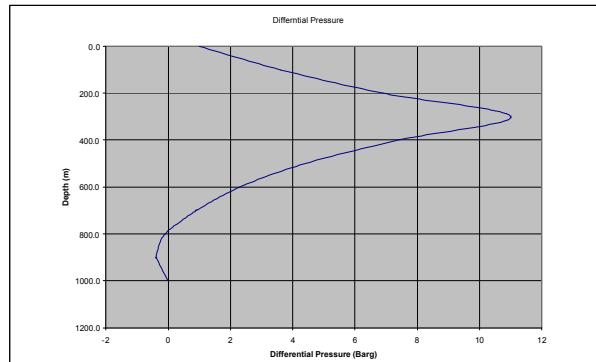


Figure 5. Differential Pressure V's Depth

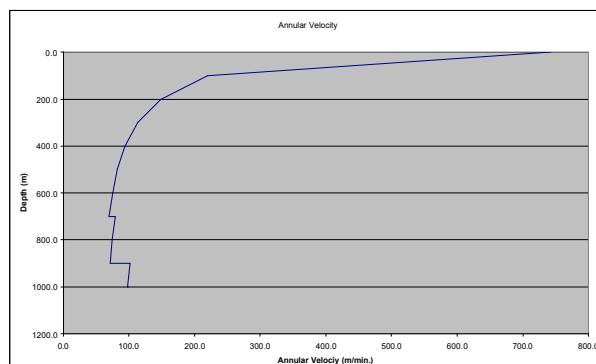


Figure 6. Annular Velocity V's Depth

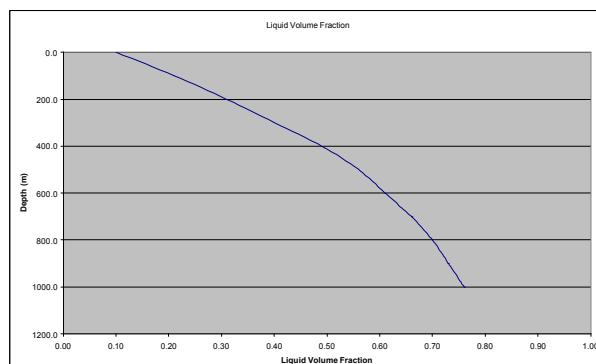


Figure 7. Liquid Volume Fraction V's depth

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 55 to 60 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.

## 6. EQUIPMENT

Although the equipment required to undertake aerated drilling operations varies with the type of fluid system selected, equipment common to all systems includes:-

### 6.1 Primary Compressors

These can be divided into two distinct types: positive displacement and dynamic. The positive displacement type is generally selected for air drilling operations and is compact and portable. The most important characteristic of this type of compressor is that any variation of pressure from the unit's optimum design, exit pressure does appreciably alter the volumetric rate of flow through the machine. Pressure increases at the discharge can be balanced by an increase in input power to produce a relatively constant volumetric output, which ensures stable conditions under a variety of drilling conditions. Positive displacement units can be further subdivided into reciprocating and rotary models. Although drilling operations originally utilised the positive displacement type; technological advances have made the rotary units even more compact and less susceptible to changes in discharge pressure, which makes them more efficient when used at the high altitudes at which many geothermal fields are located. Primary compressors typically have discharge pressures up to approximately 25 bar.

### 6.2 Booster Compressors

Boosters are positive displacement compressors that take the discharge from primary compressors and compress the air to a higher pressure (up to 200 bar). Field booster units are, in general, exit pressure (and temperature) limited. This is dependent on the inlet pressure and volumetric flowrate the booster is required to handle. As the volumetric air flowrate to the booster increases for a given booster pressure output; the booster becomes limited by its horsepower capability and similarly with an increase in output pressure.

Both primary and booster compressors should have after cooling units to reduce the temperature of their discharges. The air from the primary must be cooled to reduce the power requirements of the booster and the booster discharge must be cooled before entering the standpipe to prevent packing and equipment damage. Intercoolers are also installed between stages in multi stage units.

### 6.3 Fluid Injection Pumps

When undertaking mist or foam drilling operations, small triplex pumps are used to inject water (and foaming chemicals) into the air supply pipework at a controlled rate. These pumps generally have

capacities up to 300 lpm and have coupled metering pumps for the injection of foaming agents.

The compressor and booster units are usually independently diesel powered, skid mounted, and often silenced, each unit occupying a footprint of approximately 3 metres x 6 metres. A schematic layout of this equipment is indicated in Figure 8 below.

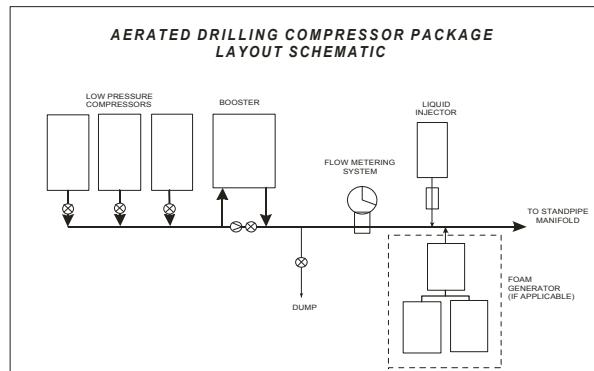


Figure 8. Aerated Drilling Air Compression Equipment Schematic Layout

## 6.4 Rig Equipment:

**6.4.1 Standpipe Manifold** - ducts the compressed air from the air supply line to the standpipe or away from the rig to the blowie line. Generally the manifold is located at floor level to allow operators to divert the air supply and to blow-down pressure in the standpipe to enable connections to be made. Figure 9 depicts a typical aerated drilling manifold.

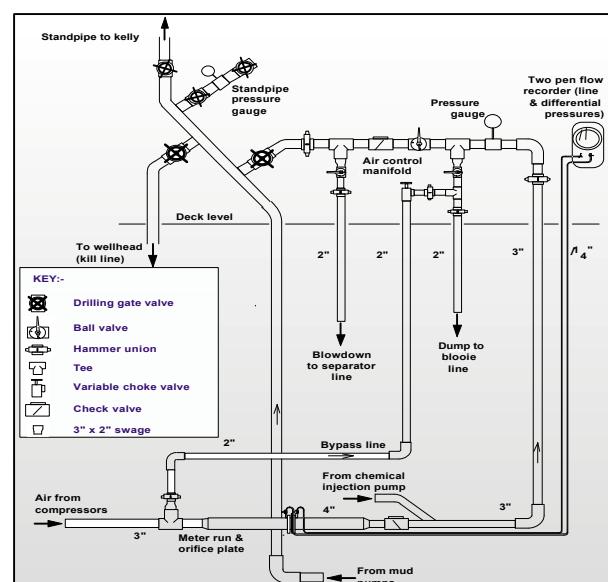


Figure 9. Aerated Drilling Standpipe Manifold Schematic

**6.4.2 Rotating Head** - is located on the top of the B.O.P. stack and contains of a packing element that rotates with the drill string and provides a seal across the annulus. The seal diverts the aerated fluid and cuttings into the blooie line. Cooling water is introduced to the rotating during drilling. prolonging the life of the packing element.

**6.4.3 Banjo Box** - a heavy walled tee which is typically located in the BOP stack above the Ram gate BOP's and below the annular/spherical BOP. The branch connection of the Banjo box is fitted with an isolation gate valve with a pressure rating equivalent to the BOP stack rating (typically API #3000). A pressure spool incorporating pressure and

temperature indicators and transducers is fitted immediately downstream of the isolation valve and is connected to the throttle or back pressure valve.

**6.4.4 Blooie line** – the pipework which carries the discharge to the air drilling separator, or bypasses the outflow directly to the drilling soakage pits.

**6.4.5 Air Drilling Separator** – a tangential entry cyclone separator, usually mounted on an elevating framework skid which provides for gravity flow of separated water and cuttings to flow from the bottom outlet to the rig shale shakers.

Figure 10. depicts a typical aerated drilling BOP stack, blooie line and separator layout schematic.

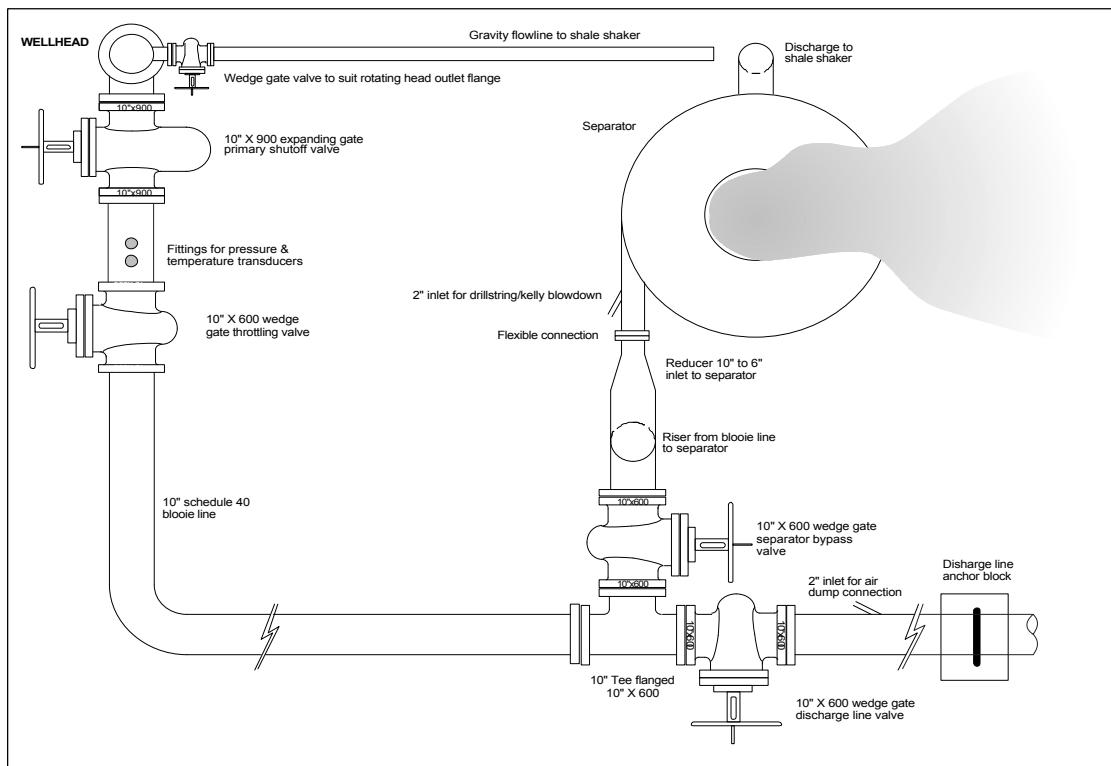


Figure 10. Aerated Drilling Wellhead, Blooie line, and Separator Schematic.

## 6.5 Downhole Equipment:

**6.5.1 Float Valves** - consist of small diameter poppet or flapper type valves that are inserted inside the drill pipe or collars and act as check valves for reverse air flow. One float valve, the near bit float valve is run immediately above the drill bit, preventing the plugging of the bit by halting any backflow of cuttings into the string during connections and stoppages in air supply.

A series of string float valves are run in the drill pipe as a safety precaution to prevent blow back of hot fluid and steam to the rig floor, and to decrease the connection time by keeping the aerated mixture pressurised below the top float valve. As drilling proceeds additional string float valves are added. These float valves also help reduce the time required to re-pressurise the system after a connection has been completed and keep the fluid moving around the bit while the connection is being made.

**6.5.2 Bottom Hole Assemblies** - In general, the drillpipe and in particular bottom hole assemblies for aerated drilling are the same as those used in standard mud or water drilling operations.

**6.5.3 Bits** – There are no special requirements bit requirements for aerated drilling, however, the higher downhole temperatures experienced often reduces the life of drill bits. Particular care is required when tripping a new bit into the hole to ensure fluid is periodically circulated through the drill string to aid in cooling.

Recently, PDC bits have proven very successful in particularly hot hole conditions. Without bearings or elastomeric bearing seals the PDC bit is impervious to higher downhole temperatures.

**6.5.4 Jet Subs** – Aerated drilling operation carried out during the 1980's and early 1990's often utilised jet subs to aid in unloading the well. Unloading is the process of replacing un-aerated fluid in the hole with aerated fluid, achieving a return of fluids to the surface, and establishing a stable circulating regime. In resources with particularly low static water levels, this unloading process can be time consuming. A jet sub was typically located in the drill string some distance above the production casing shoe. The relatively small volumes of compressed air bled into the annulus through the jet sub assisted in aerating the fluid in the hole close to the static water level, and providing lift to this cold cap of fluid, aiding the unloading process.

In recent years with larger and more efficient compression packages the use of jet subs has diminished.

## 7. ENVIRONMENTAL IMPACT

There are two sources of impact that could be interpreted as different or additional to the existing impacts of a geothermal drilling operation.

**7.1 Noise** – The large compressor and booster units provide an additional and significant source of noise. These units are fitted with very large cooling fans which are the primary noise source. However, compressor and booster units can now be provided with full silencing to accepted noise emission standards.

**7.2 Drilling Fluid and Cuttings Returns** – aerated drilling allows for full return of drilling fluid (water) and cuttings to the surface while drilling the permeable production section of a well, in comparison, no cuttings or fluid is returned to the surface while drilling the production section of a well drilled blind with water. Aerated drilling results in a significantly larger volume of cuttings is deposited in the drilling cuttings pit.

A surfactant or foamer is usually added to the circulating water to inhibit the separation of the air from the water – the process termed ‘breakout’. This foamer can cause considerable accumulation of foam in the soak pit and mud tanks. While the foam may be unsightly, it is totally biodegradable and harmless.

## 8. THE COSTS

The cost of any drilling operation or component of the operation is dependant upon the contract and risk regime in place. For cost analysis purposes the most definitive regime is the standard unit time rate contract structure, where the owner / operator carries full operation risk. This form of contract structure is currently the most common.

Typically the cost of the aerated drilling services component will be in the order of 6% of the total cost of a geothermal well.

As an example; a deviated well recently drilled in a New Zealand Geothermal field to a depth of 2600 m, with a 9 5/8" production casing shoe set at 980 m depth, and the production section drilled with an 8 1/2" drill bit with aerated fluids, took a period of 38 days to complete. The total well cost was US\$3,261,182.00, the aerated drilling services (including fuel) component of this cost US\$178,964.00 or 5.49%.

Well # 6 - 2600 m. 38 days			
Cost Code	Description	US\$ Totals	% of Total
1.000	Drill Site Preparation Costs	\$ 268,548.00	8.23%
2.000	Rig & Equipment Mob / Demob / Move	\$ 276,692.50	8.48%
3.000	<b>MATERIALS</b>		0.00%
3.100	Casings	\$ 244,910.72	7.51%
3.200	Casing Accessories	\$ 37,894.50	1.16%
3.300	Wellhead Equipment	\$ 36,686.90	1.12%
3.400	Drilling Mud Materials	\$ 32,647.80	1.00%
3.500	Drill Bits	\$ 109,598.82	3.36%
3.600	Thread Compounds	\$ 857.50	0.03%
3.700	Cementing Materials	\$ 105,406.51	3.23%
3.800	Fuel (Excluding Aerated Drilling Fuel)	\$ 146,050.45	4.48%
4.000	<b>Drilling Services Contractor</b>	\$ 799,811.46	24.53%
5.000	Top Drive	\$ 112,913.04	3.46%
6.000	Cementing Services	\$ 95,981.16	2.94%
7.000	Directional Drilling Services	\$ 77,365.22	2.37%
8.000	Mud Logging Services	\$ 61,544.00	1.89%
9.000	Mud Engineering Services	\$ 26,985.51	0.83%
10.000	<b>Aerated Drilling Services (including Fuel)</b>	\$ 178,964.61	5.49%
11.000	Rentals - Drilling Tools	\$ 54,437.02	1.67%
12.000	Miscellaneous Services	\$ 100,240.00	3.07%
13.000	Inspections, D/P Hardbanding, & Replacement, & LIH	\$ 73,160.14	2.24%
14.000	Geothermal Specialist Consultants	\$ 117,386.50	3.60%
15.000	Well Measurements	\$ 62,300.00	1.91%
16.000	Management Overheads	\$ 240,800.00	7.38%
<b>TOTAL DRILLING COST</b>		<b>\$ 3,261,182.36</b>	<b>100.00%</b>

Table 3. Typical Cost Breakdown of a Geothermal Well

Table 3. details the total well cost breakdown, and Table 4. details the Aerated Drilling Services costs.

It is interesting to note that the major cost component of Aerated Drilling Services is the Equipment Standby

– the aerated drilling package operated for only 13 days of the total period of 38 days drilling plus 3 days rig moving.

Aerated Drilling Cost Breakdown				
Cost Item	Description	Qty	US\$	%
10.000	<b>Aerated Drilling Services</b>			
10.010	Mobilisation	1.0	\$ 5,072.46	3%
10.020	Demobilisation	1.0	\$ 5,072.46	3%
10.030	Local Transport	1.0	\$ 2,800.00	2%
10.040	Equipment Standby Rate	41.0	\$ 57,483.19	32%
10.050	Equipment Operating Rate	13.0	\$ 34,949.28	20%
10.060	Operator Day Rate	33.0	\$ 25,108.70	14%
10.070	Offshore Personnel Mob Costs	1.0	\$ 2,840.58	2%
10.080	Local Personnel Mob Costs	2.0	\$ 710.14	0%
10.090	Per Diem Travell Allowances	3.0	\$ 121.74	0%
10.100	Miscellaneous A/D Charges	1.0	\$ 5,072.46	3%
10.110	Stripper Rubbers	3.0	\$ 3,804.35	2%
10.120	Foamer	3.0	\$ 1,316.75	1%
3.804	Fuel for Air Package	53250.0	\$ 34,612.50	19%
<b>TOTAL AERATED DRILLING SERVICES COST</b>			<b>\$ 178,964.61</b>	<b>100%</b>

Table 4. Aerated Drilling Services Component Cost Breakdown.

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