

## **Contribution of Underbalanced Drilling To Production Capacity at Olkaria Geothermal Steamfield in Kenya**

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**Abstract:** The planned time to drill a geothermal well at Olkaria is sometimes exceeded by a big margin when down hole challenges are encountered whilst drilling. The geographical coordinates of Olkaria are 0°53'09"S and 36°16'12"E. The current drilling practice at the field is balanced pressure drilling. The common down hole problems encountered in the field are loss of circulation, well bore collapse, minimal Rate Of Penetration (ROP) and possible formation damage which consequently leads to reduced productivity of a well. It is evident that, the longer the drilling time, the higher the cost of the well. Underbalanced drilling is the application of drilling fluids to the bore at a pressure slightly lesser than the formation fluids pressure. If the process is well executed, it may lead to the reduction/elimination of most down hole challenges. This research was geared to establishing the effectiveness of Under Balanced Drilling (UBD) in solving the down hole problems experienced at the Olkaria geothermal field. In order to carry out this exercise, simulation of under balanced drilling conditions using the Hydraulic Underbalanced Simulator (HUBS) was done utilizing data from the field. Secondly, the economics of adopting under balanced drilling technology at the field was also done. Data from four geothermal wells namely OW 731A, OW915B, OW731 and OW804 was used in the simulation exercise. Analysis of loss of circulation to well productivity for a sample of 19 wells was also undertaken. Simulated annulus volume fraction profiles showed cuttings concentration of less than 5% and an optimum circulation flow rate of 0.03 m<sup>3</sup>/min. The costs associated with loss of circulation of drilling fluids on average amounts to USD 127,731.00. Most of the wells sampled had over 70% of the drilled depth experienced no loss of circulation during drilling. Wells which had a circulation regime of full returns, partial returns and no returns have shown that their productivity is higher compared to the other categories and had an average production capacity of 12.03 Mw

**Keywords:** Underbalanced drilling, Formation damage, Rate of penetration, Loss of circulation and down hole challenges.

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### **I. Introduction**

The current drilling practice in the Olkaria geothermal field is a mixture of both overbalanced drilling, near balance drilling and balanced drilling. A geothermal well comprises of surface hole, intermediate hole, production and the open hole sections. Geothermal wells at the field have been drilled vertically and directionally. Directional wells are drilled to about 400m and then oriented to a particular direction using a mud motor which has an inbuilt angle of orientation. The drilling fluids currently used in the current drilling practice are varied depending on the section of the hole. For the surface hole and intermediate hole sections, mud is used and for the production hole section aerated fluids and foam are employed. Geothermal well drilling is usually faced by a number of down hole challenges. These challenges include loss of circulation of the drilling fluids, low rate of penetration, formation damage and reduced productivity from a well. Lack of effective hole cleanliness due to loss of circulation may lead to a stuck drill string. The time to carry out re-circulation of fluids whilst drilling has a cost factor emanating from an increase in the overall drilling time and thus impacting negatively on the cost of the well. Formation damage pertains the partial blockage of formation fractures which normally convey the steam to the well bore. These challenges can be kept to a minimum/eliminated if advanced drilling technologies are adopted. Consequently, all these challenges leads to increased drilling time, increased cost of drilling materials, increased labour cost and reduced productivity of a well. Loss of circulation is a situation which occurs when drilling fluids are not conveyed back to the surface once injected into the well bore. Factors leading to this situation are well fractured formation and the application of high hydrostatic pressure compared to the formation pressures whilst drilling. Many geothermal wells at the Olkaria Geothermal Steamfield are drilled to target depths of 3000m.

#### **1.1 Underbalanced drilling**

Underbalanced drilling is defined as drilling with the hydrostatic head of the drilling fluid intentionally designed to be lower than the pressure of the formations being drilled. The hydrostatic head of the fluid may

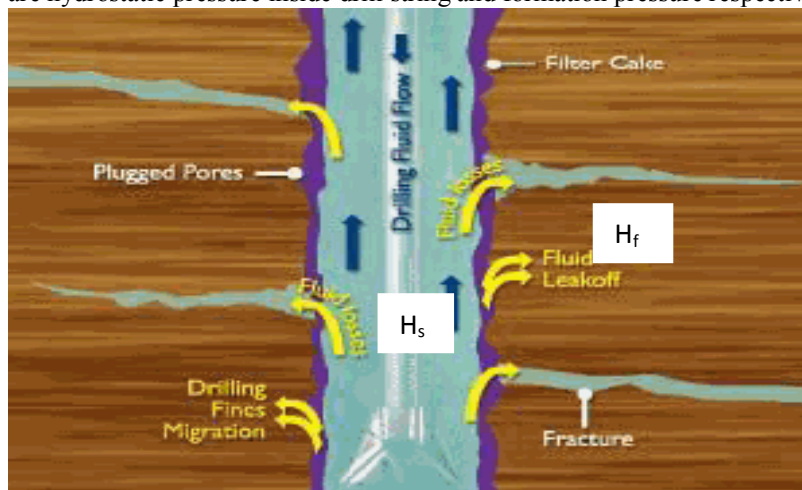
naturally be less than the formation pressure or it can be induced. The induced state may be created by adding air to the liquid phase of the drilling fluid. Whether the underbalanced status is induced or natural, the result may be an influx of formation fluids which must be circulated from the well and controlled at surface. Conventional drilling in this context means all other forms of drilling apart from underbalanced drilling and its mechanism is shown in Fig. 1. Equations 1 and 2 describe the operating principles of overbalanced and balanced drilling while equation 3 describes the principle of underbalanced drilling. Fig. 2 shows the mechanism of underbalanced drilling.

$$H_s > H_f \quad (1)$$

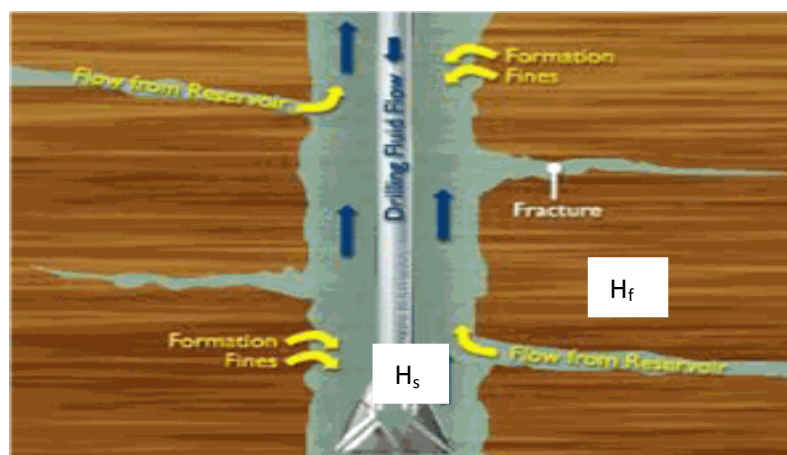
$$H_s = H_f \quad (2)$$

$$H_s < H_f \quad (3)$$

Where;  $H_s$  and  $H_f$  are hydrostatic pressure inside drill string and formation pressure respectively.



**Figure 1:** Overbalanced drilling (Putra, 2008)



**Figure 2:** Underbalanced drilling (Putra, 2008)

### 1.2 Loss of circulation

Loss of circulation can either be partial or severe. When drilling into a permeable ‘under pressured’ zone, 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 cuttings being washed into the formation as well (Hole, 2008). This loss is harmful for several reasons (Finger and Blankenship, 2010):

- If the drilling fluid fails to clean the hole and return cuttings to the surface, the cuttings can fallback on the bottom-hole assembly (BHA) and may result in a stuck bottom-hole assembly.
- Drilling fluid, especially mud, is expensive and losing it to the formation instead of re-circulating it is costly.

- In geothermal wells, the production zone is usually a lost-circulation zone, so it is sometimes difficult to cure a harmful lost circulation zone while preserving its productive potential.
- Lost circulation can suddenly lower the fluid level in a well. Decreasing the static head of drilling fluid in a hot formation can allow the formation fluids, gas, hot water or steam, to enter the wellbore, causing a kick or a blow-out. This can occur either in productive or nonproductive zones. In zones that are not hot enough (under 220°C for high temperature utilization), the lost circulation should be “sealed” to provide a wellbore that can be cased and cemented to the surface, or the cementing process should be designed to accommodate the loss of circulation to ensure a good cementing job. Adequately cementing a casing through lost circulation zones is a major problem and can be costly.
- Placement of lost circulation material (LCM) is difficult because the top and bottom of the loss zone are often not well known. The LCM or cement being used to heal the loss zone are especially likely to migrate away from the targeted placement zone if drilling has continued well past it into another loss zone, or if there is a considerable rat hole below the original loss zone.

### 1.3 Geothermal drilling fluids

Drilling fluids range from liquids, air, foam, mud and aerated fluids. The surface hole and intermediate hole sections are drilled with water based mud while the production and open hole sections are drilled either with aerated water with foam or water depending on the prevailing conditions. In foam drilling, a stable foam is generated if more liquid and a surfactant is added to the fluid. Fluid flowing from the bit exerts a jetting action that keeps the face of the hole and edges of the bit clear of cuttings. This prolongs the life of the bit and improves drilling efficiency. Fluid selection must be based on fluids compatibility, borehole cleaning and stability, temperature, corrosion effects, and environmental issues (Guimerans et al, 2001).

According to Chemwotei, 2011, the functions of drilling fluids is to clean the hole while drilling, to cool the bit, provide power to the mud motor and measuring-while-drilling (MWD) tool, support the walls of the hole, lubricate bit and drill string and control the well pressure (prevent the well from flowing). Circulation of mud is done to optimize on bentonite usage. The quantities of bentonite used are reduced by the re circulation of the mud into the fluid system. Mud is conveyed from the cellar to the shale shakers by use of a pump or any other available means. The shale shakers which are basically vibrating screens separate the cuttings and the mud is returned back to the system. Water is also re-circulated back to the system once it cools down at the circulation pond.

### 1.4 Geothermal well design

The main factor that influences the design of a geothermal well is the geological formation of the area. The design of a geothermal well involves formulating the drilling program, casing design and a cementing program. Geothermal wells may be drilled vertically or directionally with almost the same casing design. An example of the design of a geothermal well is shown in Fig. 3.

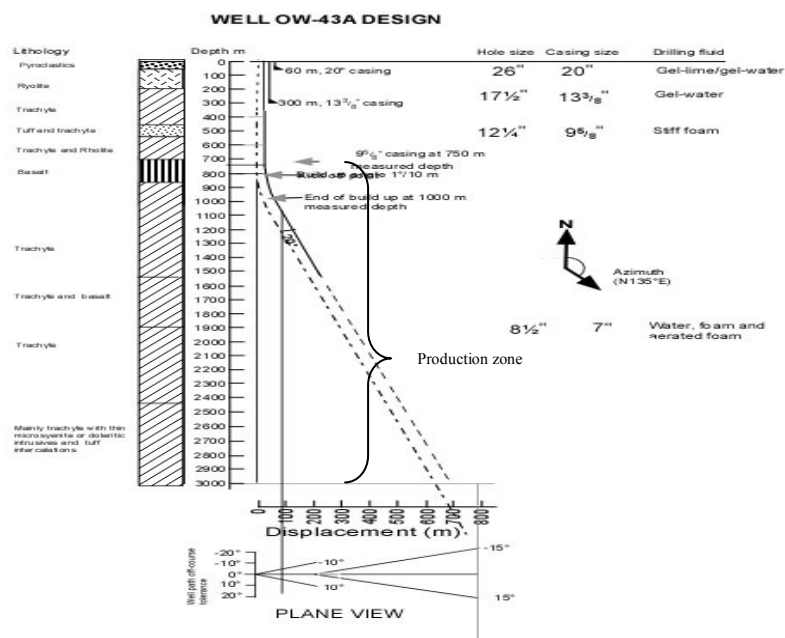


Figure 3: Design of a directional well

### 1.5 Geology of Olkaria Geothermal Steam field

The geothermal resource is associated with an area of Quaternary volcanism in which rhyolites dominate. According to Odongo, 1984, the youngest volcanic rocks are ashes, pumiceous obsidian rhyolites, vent breccias and agglomerates. The massive rocks are often capped by obsidian skin of probably the same composition as the comendites. The Ol-Njorowa gorge formation made up of tuffs and sediments shows a thickness of well over 100 m in the gorge and up to 155 m in the bore field. The unit appears to thicken towards Mt. Longonot, with much of the trachytes covered by the series of beds of pyroclastics and sediments (Odongo, 1984). The structural pattern of the Olkaria geothermal area is characterized by the following fault trends: N-S, NW-SE, NNW-SSE, and ENE-WSW (Omenda, 1998). The stratigraphy of the area is as shown in Fig. 4.

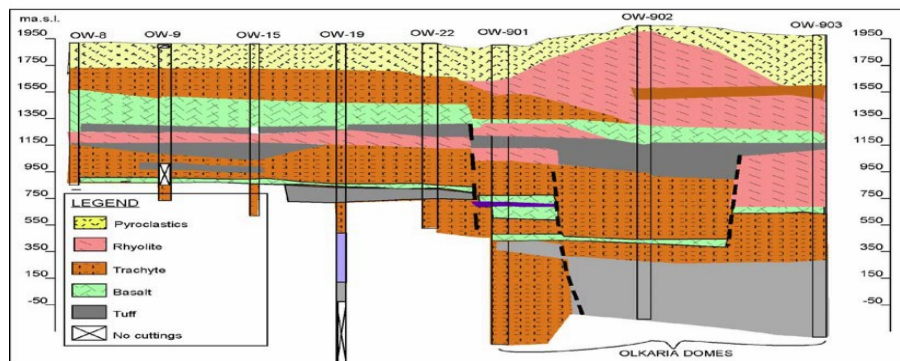


Figure 4: Stratigraphy of the Olkaria Geothermal Steamfield (Mungania, 1999)

### 1.6 Economic evaluation criteria

The benefits and the costs of the project were evaluated to determine whether the technology is economic or not. The criterion which was used is the net present value and benefit/cost ratio. These evaluation criteria are all calculated in a different manner and they may not result in a consistent ranking of alternatives. The decision criteria is that if a benefit/cost ratio is greater than one, it indicates that a project is economic; and the higher the benefit/cost ratio is, the more economical the alternative is. Conversely, with a benefit/cost ratio of less than one, a project would be uneconomic. In choosing between mutually exclusive projects; select the project with higher benefit cost ratio (Pearce et al., 2006)

$$\text{NetPresentValue(NPV)} = \sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0 \quad (4)$$

Where;

$C_t$  = net cash inflow during the period,  $C_0$  = initial investment,  $r$  = discount rate,  $t$  = number of time periods

$$\text{Benefitcostratio} = \frac{\text{Presentvalue (Discountedbenefits)}}{\text{Presentvalue (Discountedcosts)}} \quad (5)$$

## II. Methodology

Simulation of underbalanced drilling operations was undertaken for four geothermal wells namely OW 731A, OW 915B, OW 804 and OW 731. The parameters looked into are rate of penetration, formation pressures, drilling time, drilling cost savings for the various hole sections both in overbalanced drilling and in underbalanced drilling cases and the potential for production increase. Reservoir characteristics as well as formation characteristics were considered. The material consumption for wells drilled conventionally at the Olkaria field such as Bentonite and water, were computed in order to establish the cost saving in terms on drilling materials utilization. In order to determine the effectiveness of underbalanced drilling in solving down hole problems, simulation of underbalanced drilling operations was carried out using the Hydraulic Underbalanced Simulator. The parameters used in the simulation exercise include drill string sizes, the drilling fluids, formation type and formation pressures.

The Hydraulic Under Balanced Simulator (HUBS) offers calculations on pressure, velocity and cutting accumulation prediction, circulation flow rate (s) optimization, pressure matching along the flow path, underbalanced drilling with down hole motor and mud cap drilling calculations (Signa Engineering Corporation,

2012). A sample of 19 wells was considered in the study. This sample size consists of both vertical and directional wells. The wells are from the sectors of the Olkaria geothermal field which are currently under development. The major parameter looked into was the loss of circulation of drilling fluids to the formation at the production zone i.e. from 750m to 3000m depth. Daily drilling reports, well completion reports, and the wells update reports formed the basis for data collection. The sampled wells were categorized into three categories which are; wells with full and partial circulation returns, wells with full circulation returns and no circulation returns and wells with full circulation returns. A comparison of the average production capacity in Mw for the three categories was done.

### III. Data Analysis And Discussion Of Results

#### 3.1 Simulation of underbalanced drilling operations

The drilling of directional wells OW 731A, OW 915B and vertical wells OW 731 and OW 804 was simulated using the HUBS software. The Bottom Hole Assembly (BHA), the casing design and drilling fluid system used in the conventional drilling of the wells were adopted for the simulation exercise.

##### 1.5.1 Annulus volume fraction

Annulus volume consists of a water fraction, air fraction and cuttings fraction. Fig. 5 shows the simulated annulus volume fractions for four wells. For an effective under balanced drilling operation, the annulus volume fraction for cuttings should be kept below 5% (Signa Engineering corporation, 2012).

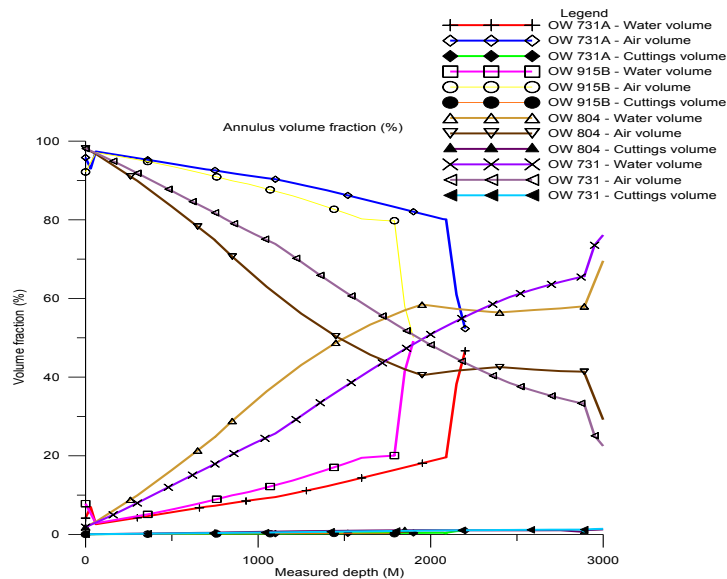


Figure 5: Annulus volume fraction profiles

The cuttings volume fraction plots for all the wells shows a very slight increase with increase in depth. The behavior of the plot is likely to be as a result of good transport of cuttings to the surface. The cuttings volume fraction in all wells simulated is below 5% of the total annulus volume as shown in Fig. 5. This is in line with the cuttings recommendation for effective underbalanced drilling. The volume fraction of water in all the wells decreases linearly as the fluid mixture travels to the surface. This could be as a result of fluid losses into the formation. The air volume fraction in all the wells is increasing linearly from deeper depth to shallow depth. This may be attributed to gas influx into the wellbore at various depths.

##### 3.1.2 Annulus velocity profile

Annulus velocities are key in determining the effects of the different fluid systems to rig equipment and components. The higher the cuttings velocity, the higher the wear rate of the rotating control head components and other well head equipment. If the velocities in the entire annulus are relatively high, the possibility is that the circulating flow rate(s) used could be well above the optimum circulating flow rate. Annulus velocities will vary depending on the type of drilling fluid in use. When using air and water, the cuttings velocity will be high as they leave the well due to rapid expansion of air at the exit. If foam is incorporated in the drilling fluid system, the velocities reduce due to the capability of foam bonding the water and air particles.



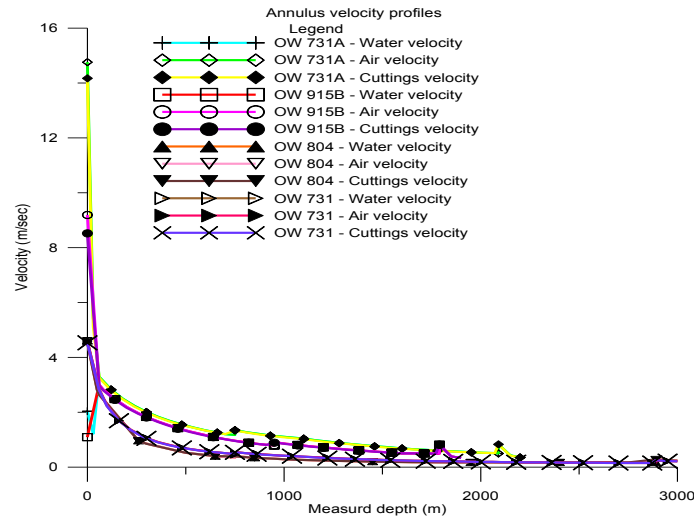


Figure 6: Annulus velocity profiles

The velocities of the three components in the annulus in Fig. 6 are increasing as the fluid mixture travel up the well bore. This may be due to accelerated inflow of formation fluids into the well bore thus increasing the velocities. The velocities of the cuttings and air also tend to increase rapidly towards the surface due to the rapid expansion of air while that of water is decreasing towards the exit.

**1.5.2 Determination of the optimum circulation flow rate, maximum cuttings concentration and minimum cuttings velocity**

The main reason for the determination of the optimum circulation flow rate is hole cleaning. Circulation of inadequate fluids causes cuttings accumulation inside the well bore, thus reducing drilling efficiency, creating down hole problems and increasing the weight of the fluid column inside the annulus. The heavy fluid column increases the bottom hole pressure and eventually result in loss of underbalanced conditions. The fall back of cuttings due to insufficient circulation rates results in reduction of drilling efficiency caused by re – grinding of cuttings by the bit in a vertical well and the formation of a cuttings bed along the section of a directional well. Circulating more fluid than required increases frictional pressure loss along the flow path, increased fluid handling equipment capacities, over consumption of power and increased erosion to the drill string and drilling equipments due the high velocities of cuttings. To maintain an underbalanced condition in the well bore requires that the drilling should operate at an optimal circulation rate and provide better hole cleaning and minimize power and equipment requirements. According to Tian et al (1999), a typical optimum circulation flow rate curve has a minimum point and the curve has a steep gradient on the left side and a less steep gradient on the right side.

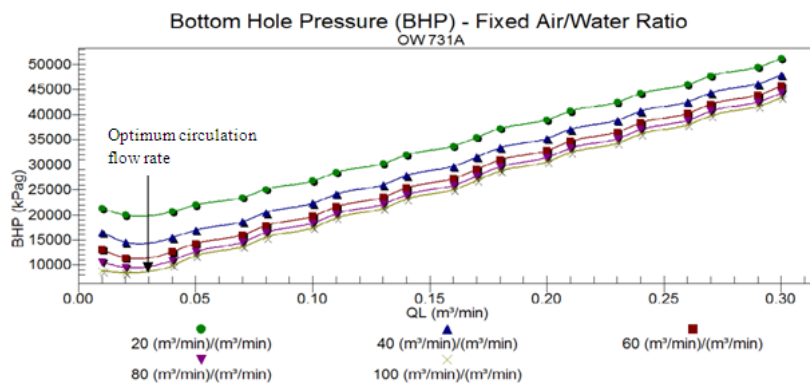


Figure 7: Optimum circulation flow rate

According to Tian et al., 1999, the optimum circulation flow rate for sufficient hole cleaning is the flow rate which corresponds with the minimum bottom hole pressure. From Fig. 7, the optimum circulation flow rate for water is 0.03m<sup>3</sup>/min. The volume flow rate interval used for the simulation was 0.0 m<sup>3</sup>/min to 0.28 m<sup>3</sup>/min.

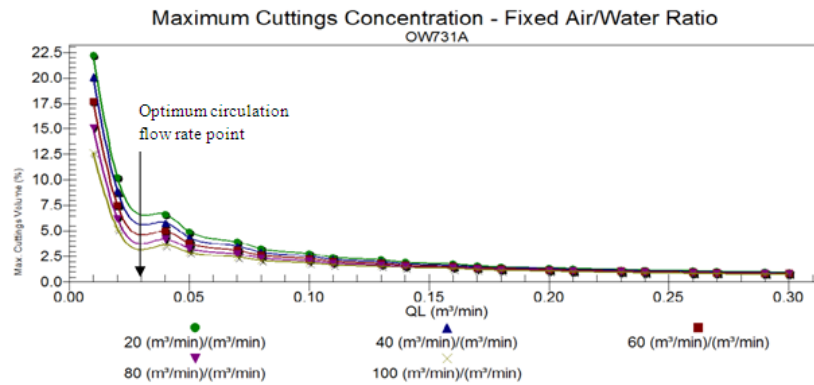


Figure 8: Maximum cuttings concentration

Circulating at a rate below the optimum circulation flow rate point may result in a sharp increase of cuttings volume in the annulus as shown in Fig. 8 and this translates into inability of the drilling fluid to effectively lift off the cuttings to the surface. Circulating at a rate above the optimum circulation flow rate point is likely to show that, the bottom hole pressure will increase due to liquid hold up in the annulus and this might lead to the fall back of cuttings to the bottom of the hole or formation of cuttings bed.

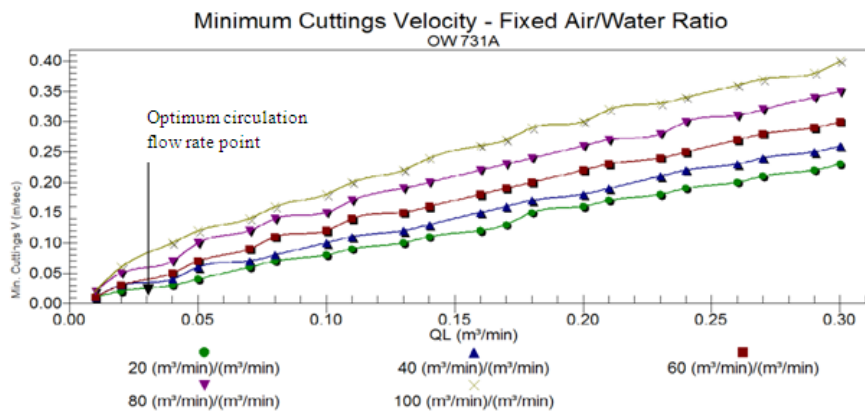


Figure 9: Minimum cuttings velocity

The cuttings velocity at the various fixed air flow rates is increasing with increase in volume flow rate of water fraction. In Fig. 9, the circulation of fluids above the optimum circulation flow rate point shows an increasing trend of the cuttings velocity. This increase in cuttings velocity is detrimental to well head equipment.

### 1.6 Analysis of loss of circulation

Loss of circulation whilst drilling may range from partial to severe. Drilling fluids are lost into the formation when these losses occur. Under normal circumstances, these fluids should be re-circulated into the well bore.

#### 3.2.1 Hole cleaning cost element

The cost element of the hole cleaning problems experienced during drilling at the field was tabulated from the daily drilling reports of the sampled wells. Hole cleaning is picked as the major problem encountered during drilling operations of the wells.

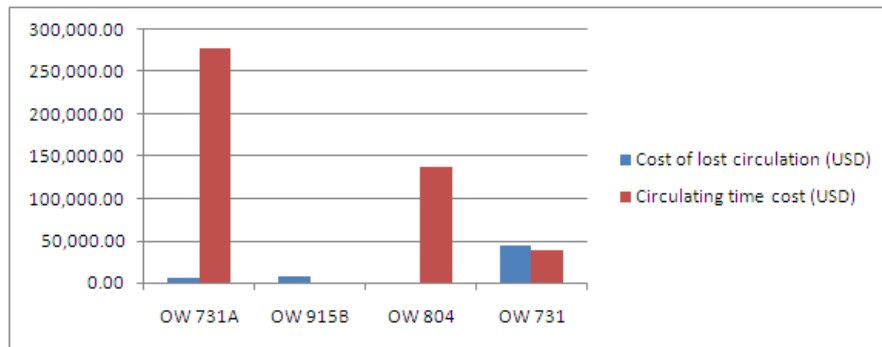


Figure 10; Hole cleaning cost analysis (Wells used in simulation exercise)

The cost element of the circulation time for well OW 731A from Fig. 10, is high compared to the rest of the wells. This could be partly attributed to insufficient transport of drill cuttings to the surface thus leading to the continuous circulation of fluids to ascertain hole cleanliness. The same well OW 731A has the lowest cost of circulation fluids incurred compared to the other three wells.

### 3.2.2 Loss of circulation compared to well productivity

The analysis was done for a sample of 19 wells selected from the Olkaria geothermal field. The covered depth was for the open hole section i.e. the production zone. Percentages were apportioned according to the form of circulation returns experienced. Most of the wells sampled had over 70% of the drilled depth experienced circulation returns during drilling. Wells which had a mixture of full returns, partial returns and no returns have shown that their productivity is higher compared to the other categories and had an average production capacity of 12.03 Mw.

Table 1: Analysis of loss of circulation

Category				MW	Field	Depth (%)		
Wells with full and partial returns (Category A)	Wells with full and no returns (Category B)	Wells with full returns (Category C)	Wells with full, partial returns and no returns (Category D)			Full returns	Partial returns	No returns
			OW 919A	6.9	Olkaria domes	83.29	14.16	2.55
OW 717				4.5	Olkaria East	94.71	5.73	-
OW 43A				6.8	Olkaria East	95.04	4.96	-
	OW 915B			11.2	Olkaria domes	81.25	-	18.75
	OW 731			9.1	Olkaria North East	82.39	-	17.61
		OW 916B		5.4	Olkaria domes	100.00	-	-
		OW 915D		6.3	Olkaria domes	100.00	-	-
		OW 915C		9	Olkaria domes	100.00	-	-
		OW 914C		6.6	Olkaria domes	100.00	-	-
		OW 723V		4.1	Olkaria East	100.00	-	-
	OW 921			8.1	Olkaria domes	86.48	-	13.52
		OW 731C		3.8	Olkaria North East	100.00	-	-
			921A	24.7	Olkaria domes	74.93	13.29	1.05
OW 733B				5.8	Olkaria North East	98.35	1.65	-
	OW 732C			3.8	Olkaria North East	97.20	-	2.80
	OW 39			9.2	Olkaria East	99.69	-	0.00
	OW 732B			4.7	Olkaria North East	81.41	-	18.59
			OW 11A	7.1	Olkaria East	94.49	1.69	3.82
			OW 46A	9.4	Olkaria East	97.02	1.78	1.20

It may also be noted from Table 1 that wells which had full circulation during drilling are not the highest producers. Four wells with full circulation during the entire drilling have their production capacities averaging 6.28 Mw. Wells which fall in the category of full and partial returns had an average production capacity of 5.7 Mw.



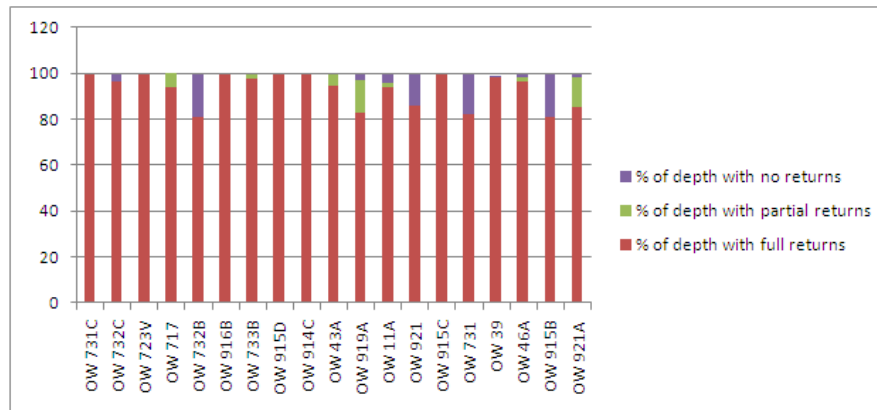


Figure 11: Circulation regimes in wells sampled

It seems that most wells from the domes field had full circulation as shown in Fig. 11 and this may be attributed to the hydro-geological setting. The wells may be had low permeability in the production zones or there was a natural underbalanced condition thus the transportation of drill cuttings was sufficiently done.

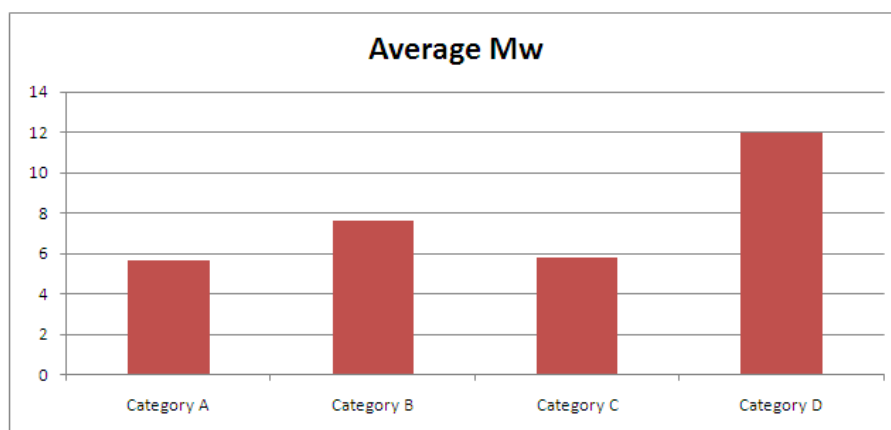


Figure 12: Comparison of average Mw to circulation regimes.

Instances of full circulation in the north east and east fields were very minimal compared to the domes field indicating more permeability, thus this occurrence distinguishes the fields as having different hydro-geological properties. According to Ouma et al, 1991, well test results had revealed two high permeability zones one along the Olkaria fault and another perpendicular to it extending southwards indicating that fault controlled permeability is important in the field.

### 1.7 Economic evaluation

The underbalanced drilling manual authored by McLennan et al, 1997, puts the increase in production from underbalanced drilling operations to be at least 10% and decrease in development costs to be at least 10%. In order to evaluate the present value of the money that is to be pumped into the alternative, three cases were considered. Case 1 is the drilling of four geothermal wells conventionally, case 2 takes into account the anticipated production increase of about 10% after drilling the four wells using underbalanced drilling and also a possible decline in production of about 4% per annum. The scenarios considered here do not take into account re-injection of condensate and brine back to the geothermal system. Case 3 takes into account that underbalanced drilling improves drilling time and wells are completed faster. This faster drilling eventually results in a decrease of development cost of about 10%. The benefit/cost ratio was also calculated so as to determine how economical the alternative is.

**Case 1** (base case): Drilling of four geothermal wells conventionally.

**Table 2: Base case**

Year			1	2	3	4
Estimated future	Operation	Units				
(1) Net production (4wells) (average 5 Mw per well)		Mw (kWh, million)	175.2	168.192	161.4643	155.0057
(2) Gross income	(1)*7ksh	Sh, million	1243.92	1194.163	1146.397	1100.541
(3) Development costs (Well cost and power plant)		kSh, million	1120	550	550	550
(4) Annual O&M cost	(1) *Ksh 0.61	ksh, million	106.872	102.5971	98.49324	94.55351
(5) Cash flow	(2)-((3)+(5))	ksh, million	17.048	541.5661	497.9034	455.9873
(6) annual present worth factor	$((1+i)/(1+d))^n$		0.919643	0.845743	0.777782	0.715282
(7) Present worth of cash flow	(5)*(6)	ksh, million	15.67807	458.0259	387.2603	326.1593

The base case shown in Table 2 considers a field development and power plant construction period of two years and plant operation for four years. The reason for this was that, drilling four wells may take at most one year to complete and construction of well head units may take also one year to complete. The minimum average output of 5 Mw for wells in Olkaria was used in this exercise. Power off take price of ksh 7 per Kwh and operation and maintenance cost of Ksh 0.61/Kwh were utilized. Interest rate and discount rate were assumed to be 3% and 12% per annum.

**Case 2**

Same as Case 1 with the exception that there is higher production due to reduced formation damage from UBD. A possible production increase of at least 10% and an annual decline of 4 % in the field was evaluated for in this case as shown in Table 3.

**Table 3: Case 2**

Year			1	2	3	4
Estimated future	Operation	Units				
(1) Net production (4wells) (average 5 Mw per well)		Mw (kWh, million)	192.72	185.0112	177.6108	170.5063
(2) Gross income	(1)*7ksh	Sh, million	1368.312	1313.58	1261.036	1210.595
(3) Development costs (Well cost and power plant)		kSh, million	1120	550	550	550
(4) Annual O&M cost(O&M cost is Ksh 0.61/Kwh)	(1) *Ksh 0.61	ksh, million	117.5592	112.8568	108.3426	104.0089
(5) Cash flow	(2)-((3)+(4))	ksh, million	130.7528	650.7227	602.6938	556.586
(6) annual present worth factor	$((1+i)/(1+d))^n$		0.919643	0.845743	0.777782	0.715282
(7) Present worth of cash flow	(5)*(6)	ksh, million	120.2459	550.3443	468.7643	398.1158

**Case 3**

Same as case 2 with the exception that development costs for the four wells are 10% less, due to improved drilling while underbalanced. The anticipated decrease in development cost was 10%. All other parameters were as for the previous cases as shown in Table 4.

**Table 4: Case 3**

Year			1	2	3	4
Estimated future	Operation	Units				
(1) Net production (4wells) (average 5 Mw per well)		Mw (kWh, million)	192.72	185.0112	177.6108	170.5063
(2) Gross income	(1)*7ksh	Sh, million	1368.312	1313.58	1261.036	1210.595
(3) Development costs (Well cost and power plant)		kSh, million	1008	550	550	550
(4) Annual O&M cost(O&M cost is Ksh 0.61/Kwh)	(1) *Ksh 0.61	ksh, million	117.5592	112.8568	108.3426	104.0089
(5) Cash flow	(2)-((3)+(4))	ksh, million	242.7528	650.7227	602.6938	556.586
(6) annual present worth factor	$((1+i)/(1+d))^n$		0.919643	0.845743	0.777782	0.715282
(7) Present worth of cash flow	(5)*(6)	ksh, million	223.2459	550.3443	468.7643	398.1158

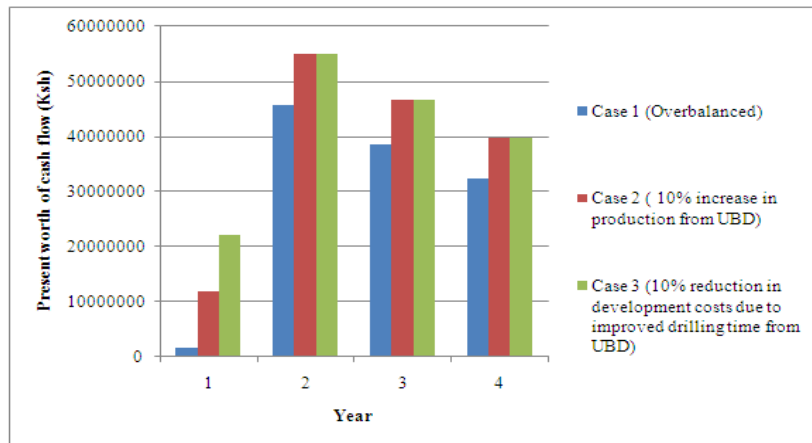


Figure 13: Summary of the three cases

In case 1, all four wells were drilled in the first year with a conventional system. Case 2 is same as Case 1 with the exception that there is higher production due to reduced formation damage from UBD. Case 3 is same as case 2 with the exception that development costs for the four wells are 10% less, due to improved drilling while underbalanced. Fig. 13 shows the net present value projections for four years of plant operation. The criteria for an economical project should have a benefit/cost ratio of greater than one. Table 5 shows how the ratio was obtained. The life span of the plant was assumed to be 30 years.

Table 5: Determination of the benefit cost ratio

Discounted construction cost (Construction period 2 years)		
Year 1	PVF (1 yr,12%) x cost in year 1	900,043,200.00
Year 2	PVF (2 yr,12%) x cost in year 2	1,315,380,000.00
Total discounted construction cost (Ksh)		2,215,423,200.00
Discounted operation and maintenance costs		
Calculating present value of annuity from year 3 to 32		
PVA (30 Yr, 12%) x Annual O&M cost x PVF (2Yr, 12%)		
		2,053,927,596.93
Total discounted costs (Ksh)		4,269,350,796.93
Discounted benefits		
Calculate present value of annuity from year 3 to 32		
PVA (30 yr, 12%) x annual benefit x PVF (2yr,12%)		
Total discounted benefits (Ksh)		17,585,298,915.57
Benefit/cost ratio =PV (Discounted benefits)/PV (Discounted costs)		
Benefit/cost ratio = 4.1		

#### IV. Conclusion And Recommendation

Volume fraction obtained in the simulation of the underbalanced drilling operation for the four wells studied here placed the percentage of cuttings at less than 5%. This means that if the wells were drilled underbalanced, hole cleanliness would have been highly achieved. Optimum flow rate ensures that the drill cuttings are efficiently transported to the surface. The value obtained here was 0.03 m<sup>3</sup>/min for the water fraction of the circulation fluid system. Circulation loss of drilling fluids helps to give an initial indication of how permeable a well is and it is also disadvantaging because it may lead to the blockage of potential production fractures. It is not a rule of the thumb that a well drilled with full circulation for the entire production hole section to produce more than a well which had a mixed lost circulation regime for the same section. Reservoir and hydro-geological properties of the geothermal system also play an important role in such a scenario. The expected result of wells under the category of full returns to be more productive than wells in the other categories was not achieved. However, a completely opposing occurrence was noticed whereby wells which had a mixed regime of circulation are the highest producers on average. The economic evaluation showed that the financial benefit of utilizing underbalanced drilling is higher in the long run compared to the conventional drilling procedures. The high benefit cost ratio of above 4.1 is a true picture of the benefits. It is recommended that under balanced drilling be considered and applied fully in the drilling of geothermal wells in the Olkaria geothermal field. Drilling personnel should also be given more detailed training in under balanced drilling procedures. Additional underbalanced drilling choke manifolds and valves should be acquired. This study also recommends more simulation of underbalanced drilling to be done using other simulation softwares so as to compare the findings.

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### **References**

- [1]. Putra M. K. A. (2008). Drilling practice with aerated drilling fluid: Indonesian and Icelandic geothermal fields. UNU GTP report 11, United Nations University, Iceland.
- [2]. Finger, J., and Blankenship, D., 2010: Handbook of best practices for geothermal. Sandia National Laboratories, report SAND2010-6048, 84 pp.
- [3]. Hole, H., 2008: Drilling fluids for drilling of geothermal wells. Presented at Petroleum Engineering Summer School, Dubrovnik, Croatia, Workshop 26, 21 pp.
- [4]. Guimerans R., Curtis F., Urbanowski R., Wilson B., Ruiz S., Fluid Selection for Underbalanced Drilling Operations, presented at the UB Technology Conference 2001.
- [5]. Chemwotei S., 2011: Geothermal drilling fluids. Report 10 in: Geothermal training in Iceland 2011. UNU-GTP, Iceland, 149-177.
- [6]. Odongo M. E. O. (1984). Geology of Olkaria Geothermal Field. Kenya Power Company report no. GL/OW/020.
- [7]. Omenda P. 1998, The geology and structural controls of the olkaria geothermal system, Geothermics, Vol. 27, No.1, pp. 55-74, 1998
- [8]. Mungania J. (1999). Summary of updates of the geology of the Olkaria Domes geothermal field. Kenya Electricity Generating Company, Ltd., unpublished report.
- [9]. Pearce D., Atkinson G. and Mourato S. (2006). Cost Benefit Analysis and the environment; recent developments. Organization for Economic Cooperation and Development (OECD) Publishing, Paris, France.
- [10]. Signa Engineering Corporation (2012). "Hydraulic Underbalanced Simulator user guide". <http://www.signa.net>
- [11]. Tian S., Finger J. T. (1999), Advanced geothermal well bore hydraulics model. Energy sources technology conference and exhibition, Feb 1-3 1999, Houston, Texas.
- [12]. Ouma P., Ambusso W., 1991, Thermodynamic and permeability structure of Olkaria North-East Geothermal Field: Olkaria fault, Annual Meeting of the Geothermal Resources Council; Sparks, NV, USA; 6 October 1991 through 9 October 1991, Volume 15, 1991, Pages 237-242.
- [13]. McLennan J., Carden R. S. and Curry D. (1997), Underbalanced Drilling Manual (GRI), GRI 97/0236