DIRECTIONAL DRILLING OF GEOTHERMAL WELLS

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ABSTRACT

Directional drilling of geothermal wells has recently become more prevalent and popular. There are some significant advantages, including increased potential for encountering permeability and therefore production; greater flexibility in selecting well pad locations relative to the well target; and it introduces the possibility of drilling a number of wells from a single well pad.
The directional drilling technology available today from the oil industry provide an array of highly sophisticated equipment, instrumentation and techniques. However, the geothermal environment is generally too aggressive to allow the use of much of it.
The most successful directional wells are those with the most simple programme.
Directional drilling provides an option to drill a number of wells from one pad providing significant cost savings. The wellhead layout on a multi-well pad is predominantly dictated by the dimensions of the drilling rig.

Keywords: geothermal, drilling, directional drilling, multi-well drilling pad.

INTRODUCTION

"Directional Drilling" is the term given drilling of a well which is deviated from the vertical to a predetermined inclination and in a specified direction. This compares with the use of "deviated" which refers to a well that is drilled off-vertical in order to sidetrack or go around an obstacle in the well.
Directional wells may be drilled for the following reasons:

- Where the reservoir is covered by mountainous terrain, directional wells can access the resource from well sites located on the easier, foothill terrain.
- Where multi-well sites are constructed and a number of directional wells are drilled to access a large area of the resource from the single site.
- Where productivity is derived from vertical or near vertical fracturing, a directional well is more likely to intersect the fracture zone at the desired depth than is a vertical well.
- Where access to a critical section in another well is required – usually from which a blowout has occurred (i.e. relief well).

Where directional wells are drilled from a multi-well site, there are the following advantages:-

- Total site construction costs are reduced.
- Road construction costs are reduced.
- Water supply costs are reduced.
- Waste disposal ponds for drilling effluent can serve a number of wells.
- The cost of shifting the drilling rig and the time taken are both significantly reduced.
- When the wells are completed, the steam gathering pipe work costs are reduced.

THE DIRECTIONAL DRILLING PROCESS

Having established the drilling target and the casing setting depths, the three dimensional geometric shape of the well needs to be determined. Typically this will be either a ‘J’ or an ‘S’ shaped well profile.

The more simple ‘J’ well shape is normally comprised of an initial vertical section to the ‘kick-off’ point (KOP); followed by a curve of constant radius determined by the "rate of build" to the end of build (EOB), following by a straight section hole at a constant angle from the vertical: (final drift angle), as is depicted in Figure 1.

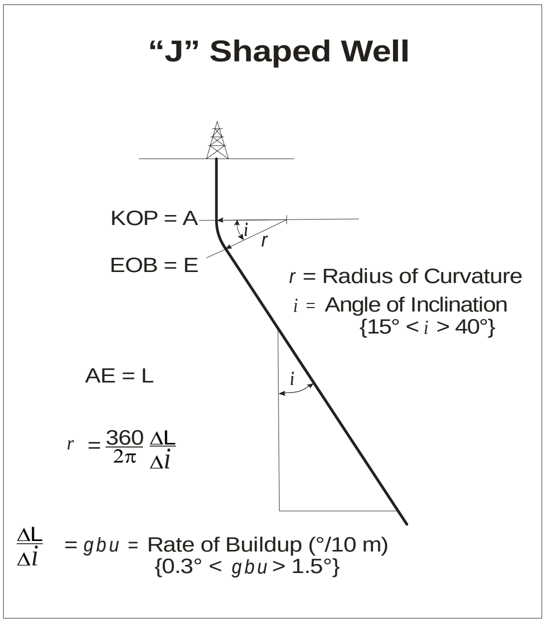

Figure 1. ‘J’ Shape Well

The ‘S’ well shape is normally comprised of an initial vertical section to the KOP; followed by a ‘build section’ with a curve of constant radius; following by a straight section hole at a constant angle from the vertical: (at the maximum drift angle); the drill bit is then allowed to fall (from the start of fall point (SOF) at a constant ‘rate of fall’ to the final drift angle, at the end of fall point (EOF); followed by a straight of hole with the drift angle being maintained at the final angle of inclination. Figure 2. depicts a typical ‘S shaped’ well.

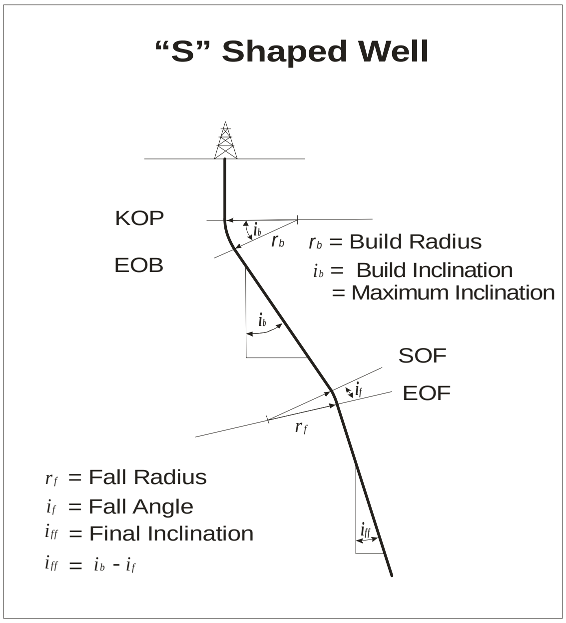

Figure 2. ‘S’ Shaped Well.

A planning well track profile, may be formulated utilising a relatively simplistic, top-down radius of curvature calculation sheet. Typically these calculation sheets are not target seeking – more sophisticated target seeking programs are utilised by Directional Drilling service companies.

Table 1. details a classic example of a simple “J” shaped well profile generated for Well MK-11 at the Mokai Geothermal Field, New Zealand.

The 13 3/8” anchor casing is set in a vertical hole at a depth of 258 m, and a 12¼” hole drilled vertically to 370 m. At this depth a mud motor is run in and the well ‘kicked-off’ with a rate of build of 2° per 30 m, with an azimuth of 110°. At a depth of 580 m MD (578 m VD), the mud motor assembly is pulled from the hole and a rotary build assembly run in. Drilling of the 12¼” hole continues to a measured depth of 765 m (751 m VD) where the maximum and final inclination of 26° is reached The 9 5/8” production casing is run in and set with the shoe at 760 m MD.

An 8½” “locked-up” rotary drilling assembly is run in and the well drilled to the final measured depth of 2400 m (2221 m VD).

The resulting target point has a lateral displacement (throw) of 806 m from the wellhead, in a direction of 110° (10° south of due East), with a final measure depth of 2400 m and a final vertical depth of 2221 m. The theoretical maximum dogleg being 2°per 30 m. The vertical section and plan of this well is depicted in Figures 3. and 4.

DIRECTIONAL SURVEY ANALYSIS

Radius of curvature method E&O E 30.00

FIELD **Mokai**
WELL No. **MK-11**
24-Nov-03
Units in METERS
Magnetic deviation -22.56 E
Azimuth True, Grid or Magnetic GRID

MEAS DEPTH (m)	DRIFT (°)	AZIM GRID (°)	VERT DEPTH (m)	COORD NORTH NZMG (m)	COORD EAST NZMG (m)	POLAR DIST (m.)	POLAR BEARING (°)	DOGLEG deg/30m
0								
0	0.00	110.00	0	6293151.07	2765363.94			
30	0.00	110.00	30	6293151.07	2765363.94	0.00	110.00	0.00
60	0.00	110.00	60	6293151.07	2765363.94	0.00	110.00	0.00
84.6	**0.00**	**110.00**	**85**	6293151.07	2765363.94	0.00	110.00	0.00
85.5	**0.00**	**110.00**	**86**	6293151.07	2765363.94	0.00	110.00	0.00
130	0.00	110.00	130	6293151.07	2765363.94	0.00	110.00	0.00
135	0.00	110.00	135	6293151.07	2765363.94	0.00	110.00	0.00
200	0.00	110.00	200	6293151.07	2765363.94	0.00	110.00	0.00
250	0.00	110.00	250	6293151.07	2765363.94	0.00	110.00	0.00
258	**0.00**	**110.00**	**258**	6293151.07	2765363.94	0.00	110.00	0.00
263	**0.00**	**110.00**	**263**	6293151.07	2765363.94	0.00	110.00	0.00
270	0.00	110.00	270	6293151.07	2765363.94	0.00	110.00	0.00
280	0.00	110.00	280	6293151.07	2765363.94	0.00	110.00	0.00
290	0.00	110.00	290	6293151.07	2765363.94	0.00	110.00	0.00
320	0.00	110.00	320	6293151.07	2765363.94	0.00	110.00	0.00
350	0.00	110.00	350	6293151.07	2765363.94	0.00	110.00	0.00
370	0.00	110.00	370	6293151.07	2765363.94	0.00	110.00	0.00
400	2.00	110.00	400	6293150.89	2765364.43	0.52	110.00	2.00
430	4.00	110.00	430	6293150.35	2765365.91	2.09	110.00	2.00
460	6.00	110.00	460	6293149.46	2765368.37	4.71	110.00	2.00
490	8.00	110.00	490	6293148.21	2765371.80	8.36	110.00	2.00
520	10.00	110.00	519	6293146.60	2765376.21	13.06	110.00	2.00
550	12.00	110.00	549	6293144.65	2765381.59	18.78	110.00	2.00
580	14.00	110.00	578	6293142.34	2765387.93	25.53	110.00	2.00
610	16.00	110.00	607	6293139.68	2765395.23	33.29	110.00	2.00
640	18.00	110.00	636	6293136.68	2765403.47	42.06	110.00	2.00
670	20.00	110.00	664	6293133.34	2765412.65	51.83	110.00	2.00
700	22.00	110.00	692	6293129.67	2765422.75	62.58	110.00	2.00
730	24.00	110.00	720	6293125.66	2765433.76	74.30	110.00	2.00
740	**24.67**	**110.00**	**729**	6293124.25	2765437.64	78.42	110.00	2.00
760	**26.00**	**110.00**	**747**	6293121.32	2765445.68	86.98	110.00	2.00
765	**26.00**	**110.00**	**751**	6293120.57	2765447.74	89.17	110.00	0.00
790	26.00	110.00	774	6293116.82	2765458.04	100.13	110.00	0.00
800	26.00	110.00	783	6293115.32	2765462.16	104.52	110.00	0.00
830	26.00	110.00	810	6293110.83	2765474.51	117.67	110.00	0.00
860	26.00	110.00	837	6293106.33	2765486.87	130.82	110.00	0.00
890	26.00	110.00	864	6293101.83	2765499.23	143.97	110.00	0.00
950	26.00	110.00	918	6293092.83	2765523.95	170.27	110.00	0.00
1000	26.00	110.00	962	6293085.34	2765544.54	192.19	110.00	0.00
1100	26.00	110.00	1052	6293070.34	2765585.74	236.03	110.00	0.00
1200	26.00	110.00	1142	6293055.35	2765626.93	279.86	110.00	0.00
1300	26.00	110.00	1232	6293040.36	2765668.12	323.70	110.00	0.00
1400	26.00	110.00	1322	6293025.36	2765709.32	367.54	110.00	0.00
1500	26.00	110.00	1412	6293010.37	2765750.51	411.37	110.00	0.00
1600	26.00	110.00	1502	6292995.38	2765791.70	455.21	110.00	0.00
1700	26.00	110.00	1592	6292980.39	2765832.90	499.05	110.00	0.00
1800	26.00	110.00	1681	6292965.39	2765874.09	542.89	110.00	0.00
1900	26.00	110.00	1771	6292950.40	2765915.28	586.72	110.00	0.00
2000	26.00	110.00	1861	6292935.41	2765956.48	630.56	110.00	0.00
2100	26.00	110.00	1951	6292920.41	2765997.67	674.40	110.00	0.00
2200	26.00	110.00	2041	6292905.42	2766038.86	718.23	110.00	0.00
2300	26.00	110.00	2131	6292890.43	2766080.06	762.07	110.00	0.00
2400	**26.00**	**110.00**	**2221**	6292875.43	2766121.25	805.91	110.00	0.00

Table 1. Mokai Well MK-11 Directional Drilling Profile

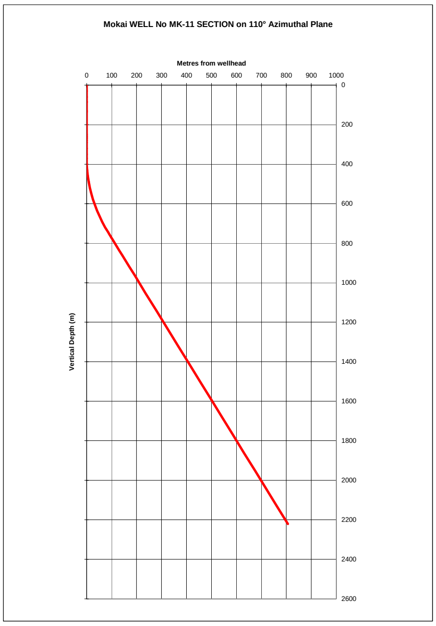

Figure 3. Well MK-11 Vertical Section

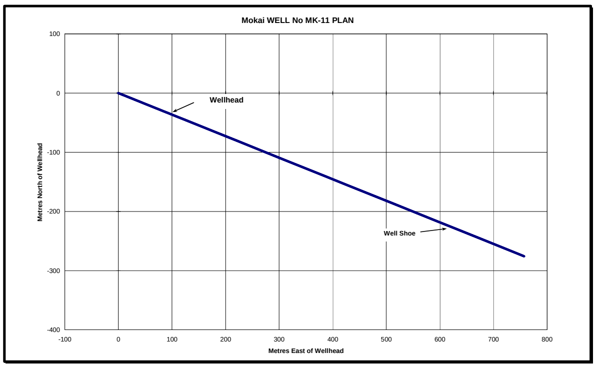

Figure 4. Well MK-11 Plan.

Table 2. details a more complex example of the "J" shaped well profile generated for Well MK-14 at the Mokai Geothermal Field. This well profile has a simple build in inclination, but adds a turn to the right just prior to the point where the maximum and final inclination is reached.

The 13 3/8" anchor casing is set in a vertical hole at a depth of 290 m. A 12¼" hole is then drilled vertically to 370 m, and the well kicked-off with a mud motor with a gentle rate of build of in inclination of 1.5° per 30 m and with the direction held constant at 30°.

At a depth of 570 m MD (568.99 m VD) the inclination is 10.0°, the tool face is adjusted and a turn to the right, at a turn rate of 3° per 30 m is initiated.

At a measured depth of 940 m MD (922.2 m VD) the final inclination of 21° is reach, and the turn to the right completed with an azimuth of 72°. The 9 5/8" production casing is set at this depth. The 8½" production hole is drilled with a fully 'locked up' rotary assembly to the final measured depth of 2400 m (2285 m VD).

The final target point has a lateral displacement of 637.6 m from the wellhead, and a final polar bearing of 67.7°. A maximum dogleg of 3.32° occurred at 760 m MD (752.5 m VD).

The vertical section and plan of this well are depicted in Figures 5. and 6.

DIRECTIONAL SURVEY ANALYSIS

Radius of curvature method E&O E 30.00

FIELD	**Mokai**
WELL No.	**MK-14**

18-Sep-06
Units in METERS
1.50 3.00 Magnetic deviation -22.56 E
Azimuth True, Grid or Magnetic GRID

MEAS DEPTH (m)	DRIFT (°)	AZIM GRID (°)	VERT DEPTH (m)	COORD NORTH NZMG (m)	COORD EAST NZMG (m)	POLAR DIST (m.)	POLAR BEARING (°)	DOGLEG deg/30m
0		30.00						
0	0.00	30.00	0.00	6293162.66	2765374.39			
30	0.00	30.00	30.00	6293162.66	2765374.39	0.00	30.00	0.00
60	0.00	30.00	60.00	6293162.66	2765374.39	0.00	30.00	0.00
85.0	**0.00**	**30.00**	**85.00**	6293162.66	2765374.39	0.00	30.00	0.00
130	0.00	30.00	130.00	6293162.66	2765374.39	0.00	30.00	0.00
135	0.00	30.00	135.00	6293162.66	2765374.39	0.00	30.00	0.00
200	0.00	30.00	200.00	6293162.66	2765374.39	0.00	30.00	0.00
250	0.00	30.00	250.00	6293162.66	2765374.39	0.00	30.00	0.00
258	0.00	30.00	258.00	6293162.66	2765374.39	0.00	30.00	0.00
263	0.00	30.00	263.00	6293162.66	2765374.39	0.00	30.00	0.00
270	0.00	30.00	270.00	6293162.66	2765374.39	0.00	30.00	0.00
280	0.00	30.00	280.00	6293162.66	2765374.39	0.00	30.00	0.00
290	**0.00**	**30.00**	**290.00**	6293162.66	2765374.39	0.00	30.00	0.00
320	0.00	30.00	320.00	6293162.66	2765374.39	0.00	30.00	0.00
350	0.00	30.00	350.00	6293162.66	2765374.39	0.00	30.00	0.00
370	0.00	30.00	370.00	6293162.66	2765374.39	0.00	30.00	0.00
390	1.00	30.00	390.00	6293162.81	2765374.48	0.17	30.00	1.50
420	2.50	30.00	419.98	6293163.60	2765374.94	1.09	30.00	1.50
450	4.00	30.00	449.94	6293165.07	2765375.79	2.79	30.00	1.50
480	5.50	30.00	479.83	6293167.22	2765377.03	5.28	30.00	1.50
510	7.00	30.00	509.65	6293170.05	2765378.66	8.54	30.00	1.50
540	8.50	30.00	539.38	6293173.56	2765380.68	12.59	30.00	1.50
570	10.00	30.00	568.99	6293177.73	2765383.09	17.41	30.00	1.50
600	11.50	33.00	598.46	6293182.50	2765386.02	23.00	30.36	1.60
630	13.00	36.00	627.77	6293187.75	2765389.62	29.35	31.26	1.63
660	14.50	39.00	656.91	6293193.40	2765393.96	36.45	32.48	1.66
690	16.00	42.00	685.86	6293199.40	2765399.09	44.28	33.90	1.69
720	17.50	45.00	714.58	6293205.67	2765405.04	52.82	35.47	1.73
750	19.00	48.00	743.07	6293212.14	2765411.85	62.07	37.13	1.77
760	19.50	51.00	752.51	6293214.28	2765414.36	65.29	37.75	3.32
780	19.17	54.00	771.39	6293218.31	2765419.61	71.71	39.09	1.57
810	18.91	57.00	799.75	6293223.85	2765427.67	81.15	41.05	1.01
840	18.93	60.00	828.12	6293228.94	2765435.97	90.47	42.89	0.97
870	19.25	63.00	856.47	6293233.62	2765444.59	99.82	44.69	1.03
900	19.83	66.00	884.75	6293237.94	2765453.64	109.31	46.47	1.16
920	20.42	69.00	903.53	6293240.57	2765460.00	115.76	47.70	1.78
940	**21.00**	**72.00**	922.23	6293242.93	2765466.67	122.31	48.98	1.82
945	**21.00**	**72.00**	926.90	6293243.48	2765468.37	123.96	49.30	0.00
970	21.00	72.00	950.24	6293246.25	2765476.89	132.27	50.80	0.00
1000	21.00	72.00	978.25	6293249.57	2765487.12	142.34	52.37	0.00
1100	21.00	72.00	1071.61	6293260.65	2765521.20	176.51	56.28	0.00
1200	21.00	72.00	1164.96	6293271.72	2765555.28	211.23	58.91	0.00
1300	21.00	72.00	1258.32	6293282.80	2765589.36	246.27	60.80	0.00
1400	21.00	72.00	1351.68	6293293.87	2765623.45	281.51	62.22	0.00
1500	21.00	72.00	1445.04	6293304.94	2765657.53	316.88	63.32	0.00
1600	21.00	72.00	1538.40	6293316.02	2765691.61	352.35	64.20	0.00
1700	21.00	72.00	1631.75	6293327.09	2765725.70	387.89	64.92	0.00
1800	21.00	72.00	1725.11	6293338.17	2765759.78	423.47	65.51	0.00
1900	21.00	72.00	1818.47	6293349.24	2765793.86	459.10	66.02	0.00
2000	21.00	72.00	1911.83	6293360.32	2765827.94	494.75	66.45	0.00
2100	21.00	72.00	2005.19	6293371.39	2765862.03	530.43	66.83	0.00
2200	21.00	72.00	2098.55	6293382.46	2765896.11	566.13	67.15	0.00
2300	21.00	72.00	2191.90	6293393.54	2765930.19	601.85	67.44	0.00
2400	**21.00**	**72.00**	**2285.26**	6293404.61	2765964.28	637.58	67.70	0.00

Table 2. Mokai Well MK-14 Directional Drilling Profile

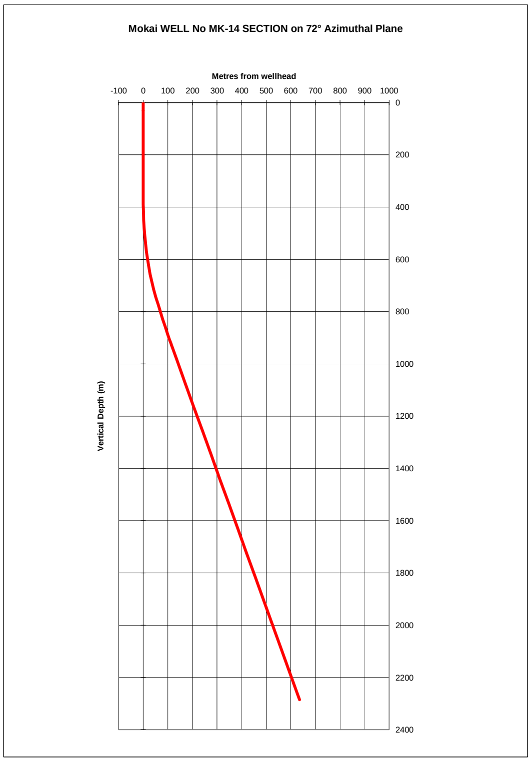

Figure 5. Well MK-14 Vertical Section

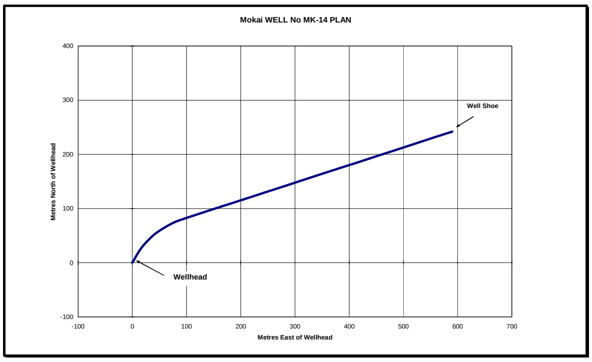

Figure 6. Well MK-14 Plan.

When these two wells were drilled the actual directional profile achieved in both wells was reasonable similar to the planned profile. However, the target depth of 2400 m measured depth was not reached in either, both being terminated at a little over 2200 m measured depth due to excessive torque and drag.
These results highlight the limitations the geothermal environment imposes upon directional drilling.

LIMITATIONS

Well design aspirations have to be tempered to what is realistically achievable. The directional drilling technology available from the drilling industry, far exceeds what is practicably useable in a geothermal environment. Simplicity of design, and of the equipment to be utilised are key to success.

- The majority of mud motors, MWD (Measure While Drilling), and downhole deviation instrumentation have operational temperature limitations of around 150°C. The KOP and initial build and directional drilling should be carried at depths where temperatures are not too high - < 150°C.
- The kick-off and the initial build and directional drilling is more efficient and more successful if carried out in a 'smaller' diameter hole – but the smallest diameter hole sections are deep and therefore hotter.
  Typically the KOP should be just below the anchor casing shoe (either 17½" or 12¼" hole section).
- Rate of build and rate of turn must be as low as possible – 1.5° to 3° per 30 m.
- A final drift angle in excess of 15° is desirable. Drift angles less than this may create difficulties in maintaining a constant direction (azimuth). Depending on the formations being drilled, a final drift angle of 25° - 35° would be common.

These limitations generally require that a significant proportion of the directional drilling must be carried out with rotary bottom hole assemblies, and that directional measurements must be made using 'slickline' instruments – retrievable tools equipped with thermal protection, run and retrieved in the drillpipe on non-electrical wireline.
Rotary bottom hole assemblies and variation of the 'weight on the bit' (WOB) and the rotary speed (RPM), can be formatted to provide build, maintain a straight hole, or allow the inclination to fall. Rotary bottom hole assemblies provide little control over the hole direction (azimuth control).

Mud motors and MWD (Measure While Drilling) instrumentation can be utilised in the upper, lower temperature hole for the kick-off, to establish a smooth and regular build in inclination – usually to a round 10° to 20°; and to establish the desired direction (azimuth).
Beyond these depths it is advisable to utilise rotary bottom hole assemblies to continue the build, hold the current angle, or allow the inclination to fall.
Typical rotary assemblies to achieve these directional requirements are shown in Figures 7, 8, and 9.

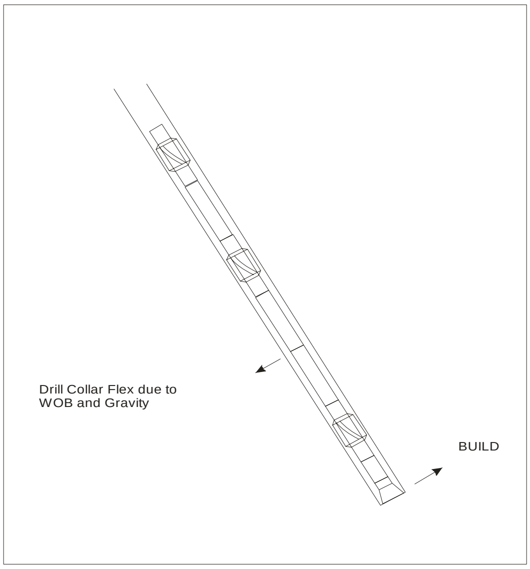

Figure 7. Typical Rotary Build Assembly

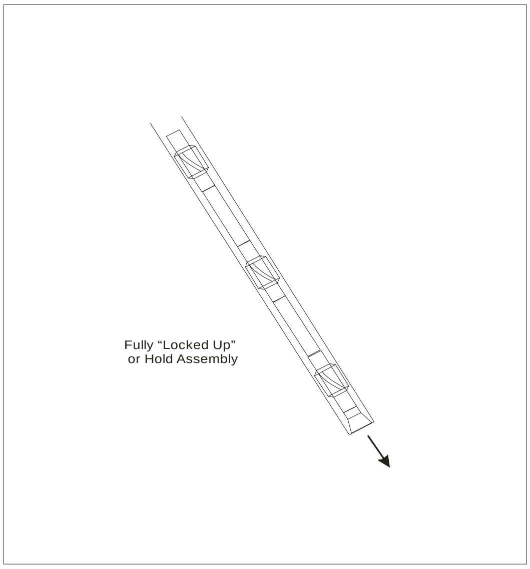

Figure 8. Typical Rotary "Hold" Assembly.

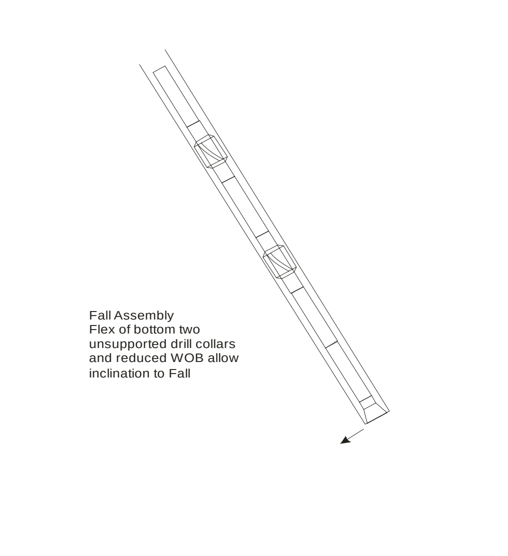

Figure 9. Typical Rotary Fall Assembly

PROXIMITY OF OTHER WELLS

Where other vertical or directional wells are in the vicinity of a planned well, the new well track proximity to open hole section of other wells must be considered.
In the extreme, if the new well track being drilled passes close to an existing productive well, such that communication between the new well and the open hole section of the existing well is possible, the potential for a blowout in the new well exits.

Of less extreme concern is possibility of production interference between wells. If the spacing between two wells drawing from the same permeable horizon is insufficient, localised drawdown can effect the productivity of both wells.

To avoid these possibilities it is desirable that the separation between the production casing shoes and the open production holes is maximised,
Typically the close approach of the production sections of any two wells should not be less than 200 m.

MULTI- WELL PADS

The ability to successfully drill directional geothermal wells has progressed to the obvious conclusion of drilling more than one well from the same drilling location. The economic savings accrue from:-

- reduced drilling pad civil construction costs – one slightly drilling pad with a slightly increased area can accommodate a number of wells. Only one access road requires construction, only one drilling effluent soak pit requires construction.
- Reduced rig moving costs – typically, the cost of moving a drilling rig from one location to another is in the order of US$500,000, taking a period of around two weeks; while a rig 'skid' from one well to the next on the same pad is generally carried out at the rig operating rate and can usually be achieved in a period of two days, at a cost in the order US$120,000.
- Reduced water supply system installation costs.
- Significantly reduced steam gathering pipework costs.

The disadvantages can be accommodated or easily mitigated.

- Live wellheads close to a drilling operation – an element of danger exists in that having completed a successful geothermal well, the rig is skidded only a distance of 5 to 10 metres from the now 'live' wellhead. There is a potential for damaging the live wellhead.
  This concern can be mitigated with the placement of a temporary protective cover over the 'live' wellhead.
- Drilling cutting soakage pits need to accommodate much greater quantities of cuttings and therefore need to be larger, and should be designed such that they can be emptied or at least partially emptied while in operation.

The well pad layout is generally dictated by the drilling rig being utilised to drill the wells, and by a rule of thumb minimum spacing of a least 5 m. such that the chance of collision in the initial vertical sections of the wells is minimised. Wellhead spacing must be such that when a well is completed, the rig can be 'skidded' or 'walked' off the well to the next wellhead, leaving the completed well accessible for completion tests, and even vertical discharge testing without significant interruption of drilling activities on the new well.
After completion of drilling of all of the wells on the well pad, there is always the possibility that workover activities may be required on any of the wells. The steam gathering pipework must be designed in such a manner that access to each wellhead is available without disconnection of adjacent wells.

AN EXAMPLE OF A MULTI-WELL PAD – MOKAI, NEW ZEALAND.

During the period October 2003 to June 2004 six (6) wells were drilled at the Mokai Geothermal Field. Wells MK-10 through MK-15 were drilled from a single wellpad designated MK-II, with Parker Drilling International Rig 188, a 2,700 HP, 1.2 million.lb, walking box base rig.
All six well were drilled directionally, with 9 5/8" production casing and 8½" diameter production hole sections.
Figure 10. is a map of the Mokai area with the well-tracks of the six production well-tracks overlaid The cased sections are indicated in grey, while the open productions are in white.

Figure 10. Mokai, Well Pad MK-II with Wells MK-10, MK-11, MK-12, MK-13, MK-14 and MK-15 as drilled Well Tracks (Cased sections indicated in grey/green; Production sections indicated in white).

The layout of the wellheads was dictated by the dimensions of the drilling rig sub-base, which was a hydraulically powered walking box base, allowing the rig to be easily walked backwards and forwards, and sideways in each direction. The box sub-base overall dimensions were 22m long by 9 metres wide, with 'hole centre' 10 m from the front toe and centred on the lateral dimension. These box base dimensions required that adjacent wells have at least a 6.0 m lateral spacing, and a 10 metre longitudinal spacing, relative to the rig sub-base.

Figure 11 is a plot of the wellhead locations on the MK-II drilling Pad.

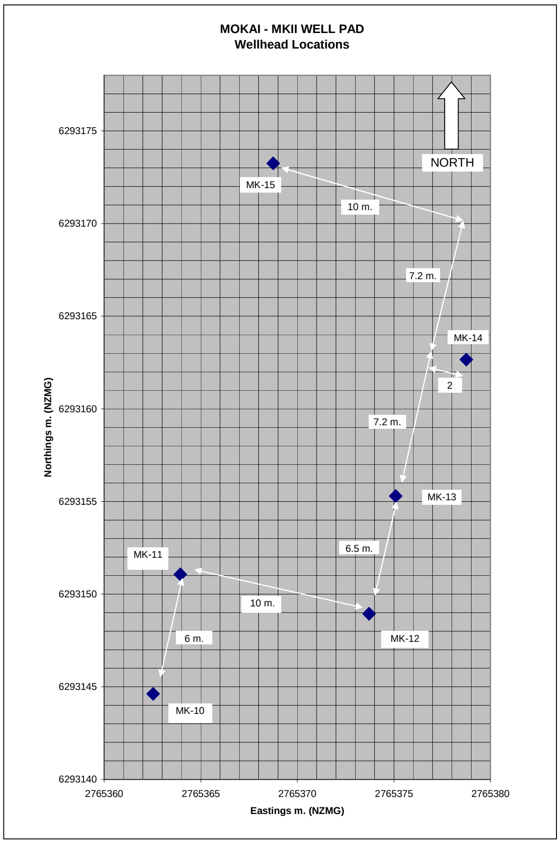

Figure 11. Wellhead locations on Mokai Well Pad MK-II

DRILLING CELLAR OPTIONS

One option which simplifies multi-well pad is to construct a single 'trough' type drilling cellar, approximately 2 metres deep with the wells spread in a single line along the trough. {Wayang Windu, Indonesia; Olkaria West, Kenya}. The wellhead and master valve being mounted such that the top of the master is just below ground level. This type of configuration allows a simple cover to be placed over the wellhead, eliminating interference to on-going drilling operations.

However, the concept of a relatively large and deep cellar has been 'de-popularised' by Health and Safety concerns relating to the possible accumulation of toxic gases.

More typically single cellars are constructed for each well, and the master-valve is mounted above ground level-requiring protective covers to put in place while on-going drilling operations continue.

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