Slim hole Drilling for Geothermal wells
For the Dutch Knowledge Agenda/
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1 Executive summary and conclusions

This report summarizes the work undertaken to investigate the feasibility of a slim hole well design for exploration drilling for ultra deep geothermal potential in the Netherlands. The Luttelgeest-01 well, drilled by Total E&P in 2004 was selected as the offset well. This well design is analyzed and three (3) slim down options are presented from which one design is recommended. The time and costs of the selected slim hole design were compared to its full hole equivalent and the risks evaluated. Finally, a short analysis of slim hole well drilling for more regular depths (3-4 kilometres) is made.

The selected slim hole well design is constructed using the following casing sizes; 20" conductor, 13.3/8" surface casing, 9.7/8" intermediate casing, 7" production liner and finally a reservoir section in 6" hole. It is believed that this is a feasible design for reaching the ultra deep targets.

The potential costs saving of this slim hole design against its full hole equivalent are estimated to be 32% or 3.4 MM EU based on current market rates. The savings are mainly realized on the purchase of casing and the following services: drilling unit, rig site construction, drilling fluids, drilling bits and solids control and disposal.

It must be understood that slimming down the well is not free of risk. There is an elevated risk of drilling induced losses that may lead to the need to set casing higher than planned. This will result in having to downsize the remainder of the well and the possibility of not being able to acquire the required data to evaluate the ultra deep targets.

As the ultra-deep geology in The Netherlands is mostly unexplored, one may not exclude the presence of deep gas accumulations which might contain H2S. With this, another high risk is the potential failure to maintain well control, as the hole is smaller in diameter, less response time is available before an influx of gas reaches critical volume. Smaller down hole tools are typically less robust than their larger equivalents, therefore the drilling process in hole sizes smaller than 8 ½" are likely to be less efficient in a hot, hard-rock drilling environment. It should also be clear that drilling a smaller hole through a potential reservoir cannot deliver (or process when injecting) the same amount of flow as its larger equivalent. Therefore the future use of a slim hole well design needs to be evaluated for each individual project.

When planning for a slim hole well for deeper targets, further detailed work is required to assess the benefits of the potential cost savings against the increase in risk and the costs of the mitigating measures required.

One further comment to be made is that drilling to ultra deep targets carries many more risks than outlined in this document as the focus here is the comparison with full hole only. When it is considered to drill ultra deep targets, proper risk assessment sessions will need to be held with all relevant parties involved. Drilling of HP/HT wells – be it slim hole or full hole – requires careful planning and execution with measures not limited to the following: sensitive flow meters, rig and supervisory personnel training in HP/HT drilling practices, thorough subsurface studies focussed on drilling hazards, additional emergency water supplies, H_2S contingency plans and equipment and involvement of local municipalities and emergency teams.

Although the main focus of this report was on the utilization of slimhole for ultra deep geothermal wells, many of the considerations given for the selection of a slimhole design also apply for deep geothermal projects. Although the cost savings for these shallower geothermal wells are likely to be considerably less, the evaluation of the consequences of a slimhole design, such as increased drilling risks, less flow potential and higher injection pressures, will also have to be done at a project level.

2 Introduction

Newell Engineering was awarded the work for the study on slim hole drilling for geothermal wells by the Kennisagenda Aardwarmte. The aim of the study is to investigate whether a slim hole geothermal exploration well is a feasible and possibly cost effective method to obtain a better understanding of the subsurface and reducing related uncertainties.

In a first stage, a general slim hole well design is made for areas with limited subsurface data and with geothermal potential. In consultation with the steering committee, it was decided to use the Luttelgeest-1 well (LTG-01) as the standard well design for which a slim hole design would be produced. With the slim hole well design evaluation, benefits and limitations a go/no go point followed. The proposed slim hole design was accepted, for this design a time- and cost estimate and comparison against a full hole design was made. Finally, a risk assessment was conducted that identified the main risks when downsizing a well to slim hole.

3 Offset well Luttelgeest-01 (LTG-01)

Luttelgeest-01 was drilled by operator Total E&P in 2004 to a total depth of 5,162m MDRT with the aim to test the Dinantian Formation for the presence of hydrocarbons. The well was drilled with the T46 land rig of drilling company KCA Deutag. A total of 141 days were spend on location to drill and suspend the LTG-01 well.

In 2005, Total E&P re-entered the Luttelgeest-01 well to perform a welltest and abandonment using the T45 rig of KCA Deutag. The following sections detail the well design and the planned versus actual operations. A total of 39 operational days were spend on the testing and abandonment of LTG-01.

3.1 LTG-01 well design

3.1.1 Casing design

For LTG-01 a 32" conductor was selected. It was driven from surface to 53m. A 26" hole was drilled to the Top Chalk at 1,131m MDRT, where a 20" casing was set and cemented in place. The 16"hole section was drilled trough the Chalk, Vlieland, Slochteren and Westphalian formations to find section TD in the Namurian C formation at 2,794m MDRT. At this point, the 13.3/8" casing was committed and cemented in place. The formations through the Namurian were drilled in 12.1/4" hole section, 9.7/8" casing was set a depth of 4,285m MDRT and cemented in place. The upper part of the 9.7/8" casing was of sour service material to counter the possible presence of H_2S. Consequently, 8.1/2" section was drilled to find total depth at 5,162m MDRT in the Devonian formation. Note that part of the 8.1/2" section was cored over the interval 4,376 – 4,379.5 and 4,470 – 4,480m MDRT. The hole was plugged back to 4,950m and a 7" liner was run and cemented.

3.1.2 Mud and cement design

The LTG-01 well was drilled with a selection of oil- and water based mud systems. Top hole was drilled with a KCL/GEM/Polymer mud system. Through the North Sea sands additions of pre-hydrated bentonite to a concentration of 10-15% were made in order to prevent seepage losses and create a good wall cake. The mud weight was raised gradually from 1.10 to 1.26sg at section TD after identifying some cavings at the shakers. The Chalk formations were drilled with a Gel/Polymer system of 1.24-1.25 sg mud weight. Prior to entering the Vlieland formation, the well was displaced to Environmul OBM. The remainder of the 16” hole section was drilled with this mud system of 1.24-1.26sg in weight. The 12.1/4” hole section through the Namurian formations was drilled with the same mud system, but the system was weighed up to reach 1.43sg at section TD. After running and cementing the 9.7/8” casing in place, the well was displaced to Thermadrill WBM, a system designed for drilling high temperature formations. A water based fluid was selected for improved kick detection. The mud weight was kept constant between 1.46-1.47sg. As down hole losses were observed ranging from 1.5 to 4 m^3/hr and drilling progress was rather slow, it was decided to continue drilling with the less expensive polymer water based mud system. During drilling, the temperature in the well would not exceed 130 °C. Prior to a trip, the well would be displaced to Thermadrill which remained stable despite the > 200 °C downhole temperature.

All casing strings were cemented with regular recipies, no light slurries were applied. All casing strings were cemented with a lighter lead (1.58-1.85sg) and heavy tail (1.67-1.92sg) in order to avoid losses during cementing or displacement and to construct a strong shoe. Only on the 13.3/8” casing job, losses were experienced which totalled to 10m^3. The 7” liner was cemented in a single recipe at 1.95sg with the addition of Fibres against the ongoing losses.

It may be worth to note that the intermediate casing and production casing were not cemented back into the previous shoe, leaving the annular space open. This was done to vent-off pressure that could build up in the annulus during drilling and production operations to exposed formations at the shoes, in order to avoid burst and/or collapse issues. When abandoning the well, these spaces need to be isolated. In addition, the well was not displaced to a water based system prior to cementing the intermediate and production casing, leaving oil-based mud above the cement. In order to isolate the annulus and to remove the OBM behind casing, additional time is required during the plug and abandonment phase.

3.1.3 Directional profile, BHA’s and drilling bits

The LTG-01 well was drilled as an S-shaped well with a maximum inclination of 21.4°. The build up was completed in the 26” hole section and the drop-off in the 16” section. The other sections were drilled vertically. The reason for the directional design was that the surface location above the target was not accessible.

The 32” conductor was drilled out with a 26” slick BHA, after which a 26” steerable motor BHA was picked up with a 115 milled tooth bit in order to initiate the kick-off. The BHA drilled to section TD and performed as planned with an average ROP of 15.3 m/hr.

The first BHA on the 16” hole section consisted of a motor and MWD with a 415 TCI bit and was designed to drill through the Ommelanden and Texel Chalk and drop the well back to vertical. It performed as planned but not with great progress at 7.1 m/hr. Once the Westphalian B was reached, the BHA was pulled to change the bit for a M323 PDC. The new bit progressed well at 11 m/hr until the point no further progress could be made. A new PDC of M422 was made-up and drilling continued at 3.5m/hr as the Westphalian firmed up. No further progress could be made after 113m AH, so the BHA was pulled and the bit and near-bit stabilizer were found to be 2.5” under gauge. It was suspected that the motor in the assembly created too much heat, burning up the bit. The next BHA was a packed rotary assembly with a M433 PDC which reached an ROP of 0.9m/hr. The motor was laid down in order to have a greater flow by area for the possible application of LCM in the Namurian C. Due to the slow progress, it was decided to call section TD 50m early.

The 12.1/4" section started off with a straight motor BHA with a M432 PDC, reaching 5.2 m/hr on average. The BHA was pulled due to slow progress, the bit was found to be worn at 2-8-RO. As the Ubachsberg Sand formation was reached, a high speed motor was picked up with an impregnated bit at M842. The BHA drilled through the hard and abrasive formation with 1.9m/hr into the Namurian B formation. Once no further progress was achieved, the BHA was pulled with the bit at 6-4-LM. The following motor BHA was made up with a M433 PDC and drilled 200m at an average of 4.2 m/hr. Again, a motor BHA with M432 bit was run and drilled 142m at an average of 2.6 m/hr. The next BHA included a roller reamer, but that could not make a difference. The M432 PDC bit drilled 293m at 2.9m/hr. Another 12.1/4" BHA was run with a M323 PDC and motor which drilled 115m at 2.9m/hr. The following BHA drilled 47m at 0.31m/hr with a M432 PDC bit. The next BHA did even worse with 16m at 1.4m/hr with a M433 PDC. It was assessed that the formation was too hard (> 28,000 psi) for PDC bits, therefore the next BHA was equipped with a TCI bit. A rotary BHA was run in hole with a 447 TCI bit which drilled 117m at 1.9m/hr. The bit was pulled because it reached maximum krevs. The bit was replaced for a new 447 TCI and the BHA was run in and drilling continued to section TD at 2.0 m/hr.

The 8.1/2" section was started with a rotary assembly with a M423 PDC which drilled 58m at 1.1m/hr. As progress was still slow, the bit was changed for a TCI at 517. This BHA reached the reservoir after 28m at 1.9m/hr. A coring BHA was picked up that cut a 3.9m core and recovered 69%. Another rotary assembly with M332 PDC was run that drilled to the second coring point with 4.6m/hr. Another 10m core was cut which recovered 33%. This time a straight motor assembly was picked up with a M332 PDC to drill to the logging point, this was done with an ROP of 5.6 m/hr. Following the logging programme, the well was drilled to TD with 3 BHA's. The first being a rotary BHA with M332 PDC reaching 1.4 m/hr. The second being a straight hole motor assembly with M431 PDC reaching 6.5 m/hr. The final drilling BHA was again a straight hole motor BHA with a 517 TCI that reached 2.5 m/hr progress.

3.1.4 Logging programme

The following electric line formation evaluation logs were run on Luttelgeest-01.

Hole size Depth	Number	Tool	Log recorded
16" hole 1,131 – 2,794 m MDRT	1.1.1	EMS-AIT-DSI-GR	Resistivity Sonic Gamma Ray Caliper
	1.1.2	IPLT	Neutron / Density
12.1/4" hole 2,794 – 3,885 m MDRT	2.1.1	VSP	Vertical Seismic Profile
	2.1.2	Walk-away VSP	Vertical Seismic Profile
	2.1.3	AIT-DSI-EMS	Resistivity Sonic Caliper
	2.1.4	Walk-away VSP	Vertical Seismic Profile
	2.1.5	IPLT	Neutron / Denisty
	2.1.6	CBL-VDL	Cement Bond Log
12.1/4" hole 2,794 – 4,290m MDRT	3.1.1	AIT-DSI-EMS	Resistivity Sonic Caliper
	3.1.2	MSCT	Sidewall cores
	3.1.3	IPLT-EMS	Neutron / Denisty Caliper
8.1/2" hole 4,285 – 4,606 m MDRT	4.1.1	FMI-GR-EMS	Imager Gamma Ray Caliper
	4.2.1	MDT Dual Packer	Pressure & Samples
	4.3.1	MDT Dual Packer	Pressure & Samples
	4.3.2	MDT Dual Packer	Pressure & Samples
	4.3.3	HNGS-IPLT	Natural Gamma Ray Neutron / Density
	4.3.4	EMS-AIT-Array Sonic-CBL	Caliper Resistivity Sonic Cement Bond Log
	4.4.1	MDT Dual Packer	Pressure & Samples
	4.4.2	MDT Single Probe	Pressure & Samples
	4.4.3	MDT Single Probe	Pressure & Samples
8.1/2" hole 4,285 – 5,162 m MDRT	5.1.1	FMI-GR	Formation Micro Imager Gamma Ray
	5.1.2	IPLT-HNGS	Neutron / Density Natural Gamma Ray
	5.1.3	QAIT-QSLT-EMS-GR	Resistivity SONIC Caliper Gamma Ray

	5.2.1	GR-MDT Dual Packer	Pressure & Samples
	5.2.2	GR-MDT Single Probe	Pressure & Samples
	5.3.1	GR-MDT Dual Packer	Pressure & Samples
	5.3.2	GR-MDT Dual Probe	Pressure & Samples
	5.4.1	GRT-MDT Single Probe	Pressure & Samples

Table 1 – Formation Evaluation Program LTG-01

Many of the drilling BHA's were equipped with Directional MWD and Gamma Ray LWD sensors in the 16" and 12.1/4" sections. The Pathfinder DFT (tester while drilling / dual packer tool) was tried on the 8.1/2" section, but it failed to work due to the high bottom hole temperature.

3.1.5 Well schematic

The LTG-01 well schematic on the next page details all the information described in the sections above.

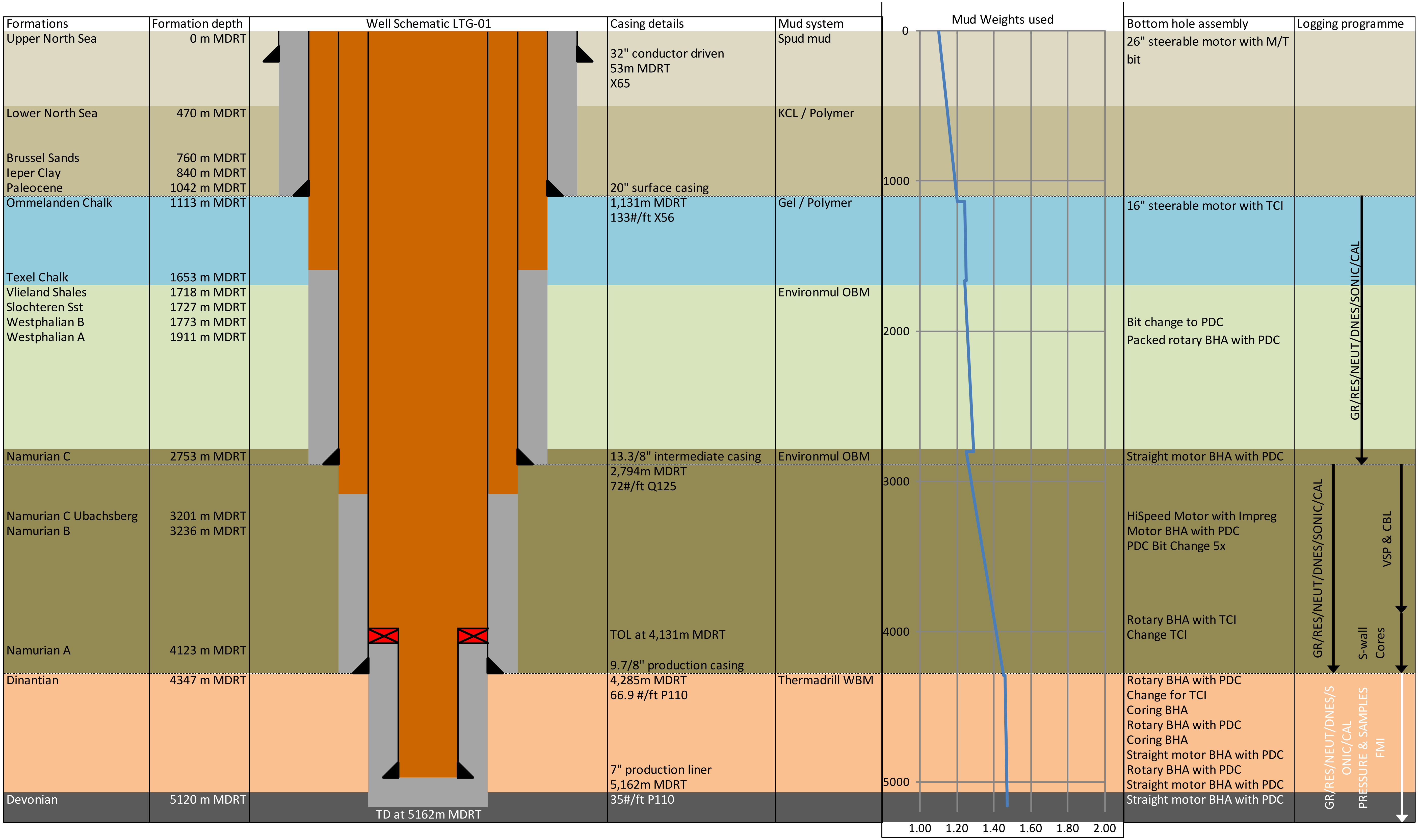

Figure 1 – Well Schematic LTG-01

4 Slim down options

The LTG-01 well was constructed using 5 strings from surface to TD (including conductor and liner). Assuming the casing seats will remain at the same points as selected by Total E&P, the slim hole design will also count 5 strings in case there is a desire to case off the reservoir section.

Looking at the minimum size of hole required in order complete a regular logging programme, one could drill as slim as 3.7/8" hole size. However, the limitation for slimming down to 3.7/8" reservoir section is that the tapered drillstring would end with 2.7/8" pipe with 3.3/8" tool joint OD. The torque limitation on tool joint is low at 15,945 ft.lbs (max. MUT is 7,100 ft.lbs)[1]. This torque rating is regarded to be too low for drilling the Dinantian formation at this depth. The risk of drill string failure would increase significantly. In addition, one would not have any contingency hole size when 3.7/8" is planned for. Note that the logging tools available for this size are limited to a basic logging suite, and are not sufficient for a thorough subsurface evaluation. This option is therefore not evaluated further.

4.1 Slim hole well design

When the LTG-01 well would be slimmed down a single size, the resulting reservoir section would be drilled in 6" hole. This leaves a contingency section of 4.1/8" hole for which the basic logging tools are available with the main contractors. With a reservoir section in 6", the well design could be slimmed down to start with a 20" conductor; a 13.3/8" surface casing and 9.5/8" intermediate casing. The production casing could be replaced by a production liner in 7". Should the contingency hole section be required, a 5" liner could be run inside the 6" hole. Should the reservoir be cased-off, a 5" liner could be run. This design will be referred to as the 'slim hole well design'.

4.2 Ultra slim hole well design

There is also the option to have a reservoir section in 4.1/8" diameter, with a contingency hole section of 2.7/8", for which no logging tools are available. This would imply that there is no contingency hole size. The well would start with a 13.3/8" conductor and have a 9.5/8" surface casing, the intermediate section will be cased off with a 7" liner and the production liner will now be 5". The reservoir section of 4.1/8" diameter could be cased off with a 3.1/2" liner if desired. This well design will be referred to as the 'ultra slim hole well design'.

4.3 Slim hole (surface liner) well design

The final option would be to replace the surface casing string for a surface liner of 11.3/4" size. The well would start off with a 13.3/8" conductor after which the 11.3/4" surface liner would be installed. From this point, the architecture will be the same as the 'slim hole well design', i.e. an intermediate casing of 9.5/8", a production liner of 7" and a 5" liner through the reservoir section. This well design will be referred to as the 'slim hole (surface liner) well design'.

[1] 2.7/8" 10.4#/ft S-135 XT27 drill pipe specifications by Workstrings Int'l.

For clarity, all designs are summarized in the table below and also depicted in the schematic below.

String	LTG-01	Slim hole design	Ultra slim hole design	Slim hole (surface liner)
Conductor	32”	20”	13.3/8”	13.3/8”
Surface Casing	20”	13.3/8”	9.7/8”	11.3/4” (L)
Intermediate Casing	13.3/8”	9.7/8”	7” (L)	9.7/8”
Production Casing	9.5/8”	7” (L)	5” (L)	7” (L)
Production Liner	7” (L)	5” (L)	3.1/2” (L)	5” (L)

Table 2 – Casing details for slim hole designs

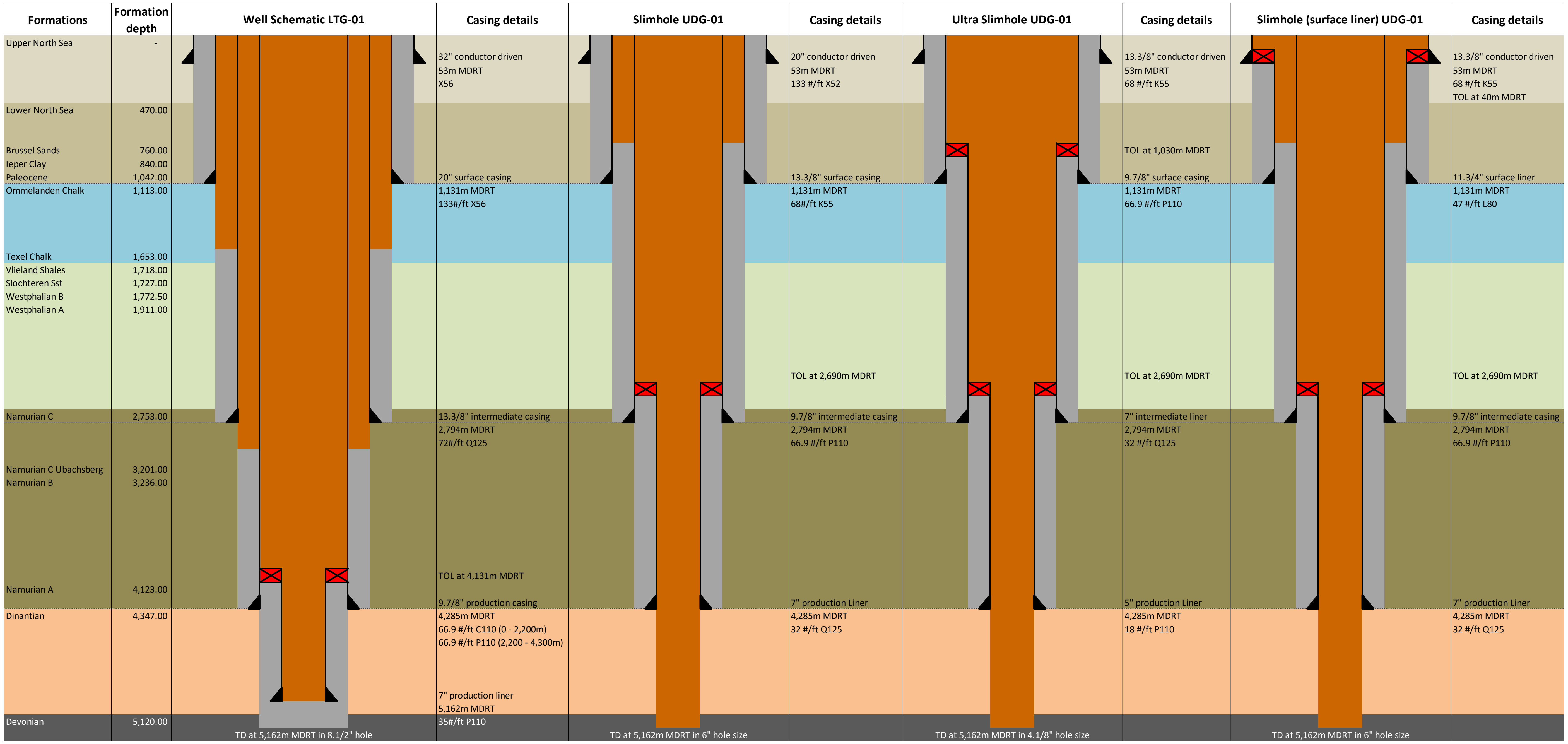

Figure 2 – Well Schematics of slim hole designs

Note; Casing details are preliminary, no actual casing design was performed.

5 Well designs

The following sections detail the differences of the slimmed down options for the LTG-01 well. The following topics are covered:

- casing design,
- liner hangers,
- underreaming,
- e-line and LWD tools,
- rental exploration wellhead,
- cement design,
- mud design and volumes.

Based on these topics, a recommended slim hole well design will be selected.

5.1 Casing design

As this study is not meant to design a specific well, it is not possible to perform a detailed casing design with specific load cases. It was therefore decided that the casing properties of the slim hole designs had to meet the properties of the LTG-01 casing strings.

In the table below, the casing string properties of LTG-01 and the slim hole designs are tabulated. For every string selected in the slim hole designs, the burst and collapse resistance are superior to the LTG-01 strings. The exception is the 7" 32 #/ft string that is selected; its collapse pressure is 6 bar less than the equivalent 9.7/8" string on LTG-01. This is not expected to be an issue for the well design, but a detailed casing design evaluation would need to prove the applicability of the strings mentioned below on an actual well anyway.

Note that for the well designs mentioned in table 3 below, the reservoir section is assumed to be cased-off. However, this may not be a requirement for exploration purposes.

String [-]	size [inch]	weight [#/ft]	grade [-]	burst [bar]	collapse [bar]	axial [mTon]	drift ID [inch]
			LTG-01				
Surface	20	129.33	X56	217	100	963	
Intermediate	13.3/8	72	Q125	580	199	1178	12.25
Production Casing	9.7/8	66.9	C110 / P110	898	814	771	8.5
Production Liner	7	35	P110	945	899	406	5.879
			Slim hole				
Surface	13.3/8	68	K55	238	134	389	12.259
Intermediate	9.7/8	66.9	P110	898	814	771	8.5
Production Casing	7	32	Q125	977	808	423	6
Production Liner	5	18	P110	961	929	211	4.151
			Ultra-Slim hole				
Surface	9.7/8	66.9	P110	898	814	771	8.5

Intermediate	7	32	Q125	977	808	423	6
Production Casing	5	18	P110	961	929	211	4.151
Production Liner	3.1/2"	9.2	P110	963	933	103	2.9
Slim hole (surface liner)							
Conductor / Surface casing	13.3/8"	68	K55	238	134	389	12.259
Surface liner	11.3/4"	47	L80	308	112	272	10.844
Intermediate	9.7/8	66.9	P110	898	814	771	8.5
Production Casing	7	32	Q125	977	808	423	6
Production Liner	5	18	P110	961	929	211	4.151

Table 3 – Casing details of slim hole designs

5.2 Liner hangers

The LTG-01 well included a single liner hanger system for hanging-off and isolating the annulus of the 7" liner inside the 9.7/8" casing. Taking into account the reservoir production liner, the 'slim hole design' counts two liner hangers; a 7" liner hanger and a 5" liner hanger. The slim hole (surface liner) design makes use of the same liner hangers as the 'slim hole design' plus an 11.3/4" liner hanger. The ultra slim hole design also requires the same liner hangers as the slim hole design plus a 3.1/2" liner hanger for the reservoir production liner.

A market inquiry has proven that the 3.1/2" liner system is not available as standard equipment. A solution to that could be engineered with a liner hanger with production packer above in order to seal-off the annulus, but this is not recommended.

5.3 Underreaming

Of the described designs, the slim hole (surface liner) is the design that carries the need to underream the top hole and intermediate section. The drift ID of a usual 13.3/8" casing is 12.1/4", which is too small for an 11.3/4" liner to be installed in. This means that the hole below the 13.3/8" conductor needs to be opened-up to a larger diameter using an underreamer. This tool has a cutting structure that will expand beyond the hole diameter with the hydraulic force of the mud pumps and enlarge the hole diameter to a preset value. Once the pumps are shut-off (at section TD for instance), the cutting structure is retracted and the tool can be pulled through surface through the smaller ID casing. The 12.1/4" hole below the 13.3/8" conductor would have to be underreamed to 14.1/2" for instance.

The same issue applies to the intermediate section as the maximum hole diameter through the 11.3/4" liner is 10.5/8". It would be very challenging running a 9.7/8" casing to bottom in this hole, and impossible to cement it. To solve this issue, the 10.5/8" hole would need to be underreamed to 12.1/4".

Applying this slim-hole design would imply underreaming approximately 2,700m AH in two sizes. Not only does this add cost in terms of tool rental, it also sets back the rate of penetration (drilling progress). Underreaming the surface hole would not pose many issues theoretically from a formation point of view. The intermediate section however, includes the Chalk, Westphalian and Namurian formations with the risk of Chert beds and hard rock drilling, leading to (very) low progress as reported on LTG-01. Multiple trips for the underreaming tool would need to be accounted for.

Note that the 11.3/4" liner would need to have flush connections in order to be run through the 13.3/8" conductor. It is recommended that the 9.7/8" casing would have (semi-)flush connections as well, the clearance with small size connections is too low and creates too much surge on the formation when running in hole and back-pressure during the cement job.

Note that the 'slim hole design' and the 'ultra slim-hole' design do not require underreaming.

5.4 Cement design

A cementing contractor was approached for performing a cement placement study for the slim hole design as presented in section 3.3. Unfortunately it proved to be rather difficult to provide such support without the commitment of actual work. It was therefore agreed to perform a qualitative analysis of the cement design of the slim hole design.

The provided feedback can be summarized as follows; *no specific challenges are to be expected with the provided cement design. The selected casing design is much in line with how wells in the Netherlands are constructed in general – except for the fact that 10.3/4" and 7.5/8" MUST casing are run.*

Note that the 10.3/4" and 7.5/8" reduce the annular clearance further than 9.7/8" and 7" in a similar hole size. Theoretically it would therefore be easier to achieve a cement job without losses as there would be less friction pressure on the formation.

5.5 Mud design

As there is no actual well design for this study, the LTG-01 well was considered for the slim hole designs. From the final drilling report of LTG-01, it was concluded that the mud design is adequate. There was therefore no reason to change this for any of the slim hole designs. There is off course a difference in mud volume requirements, which is quite significant. This could also impact the selection of the drilling rig.

Mud type [-]	OHXS [%]	LTG-01 [m^3]	Slim hole [m^3]	Ultra-slim hole [m^3]	Slim hole (surface liner) [m^3]
Spud mud	30%	725	300	175	225
KCL/Polymer	20%	1625	625	375	500
Gel/Polymer	10%	1225	550	300	475
Environmul OBM	10%	1775	875	450	825
Environmul OBM	10%	1425	675	425	675
Thermadrill	10%	850	600	400	600

Table 4 – Mud volumes requirements for slim hole designs

Note; a safety stock of 25 m^3 is included in the mud volumes above, as required by some rig contractors.

Also, the amount of rock that needs to be drilled trough – and disposed-off – is quite different as is evident from the table below.

Cuttings [-]	LTG-01 [mT]	Slim hole [mT]	Ultra-slim hole [mT]	Slim hole (surface liner) [mT]
WBM cuttings	5847	2439	1355	2127
OBM cuttings	2894	1560	762	1560
Total cuttings	8740	3999	2117	3687
OBM skips	579	312	152	312

Table 5 – Cutting volumes slim hole designs

Note; an average rock specific gravity of 2.6 and a cutting skip capacity of 5 mT was assumed.

5.6 E-line and LWD tools

From logging contractors' websites inquiry, it seems that all tool required for running a comparable logging programme as LTG-01 are available for holes as small as 3.1/2". These tools are generally suitable for high temperatures > 200°C.

To save operational time, to make decisions while drilling and to have shorter durations between drilling and casing-off, many holes are logged while being drilled (Logging While Drilling; LWD). For this, LWD tools for a full suite of logs are available at the major contractors. The smallest size tools are of 4.3/4" body with which a 5 7/8"- 6" hole can be drilled. In general, these tools have an operational limit of 200°C. These could be used on the slim hole and the slim hole (surface liner) well designs. The reservoir section of the Ultra slim hole design is too small (4.1/8") for LWD measurements.

5.7 Wellhead and Christmas trees

With the major wellhead and tree suppliers, a wide range of wellheads and trees are available to accommodate the well designs presented in section 3. For all the well designs, it holds that there may be the necessity that the surface hole is to be drilled under the protection of a diverter system that will be installed over the conductor in case the possibility of shallow gas cannot be ruled-out. Once the surface hole section is drilled and cased-off safely, the wellhead can be installed and subsequently the BOP will be nippled up. Various sizes of base plates and starter heads are available including appropriate sizes for the 9.7/8" or 13.3/8" surface casing.

It should be noted that pressure rating of the starter head (and consequent casing heads or spools) needs to be considered. The rating is based on the maximum expected surface pressure. As no true well design is considered for this study, the burst rating of the exposed casing string below the wellhead for a specific hole section reduced by a gas column, will dictate the pressure rating of the wellhead. This means that the slim hole designs require the following wellhead ratings.

String	Slim hole design		Ultra slim hole design		Slim hole (surface liner)	
Surface hole	20”	N/A	13.3/8”	2 K psi	13.3/8”	3 K psi
Intermediate hole 1	13.3/8”	3 K psi	9.7/8”	13 K psi	11.3/4” (L)	8.5 K psi
Intermediate hole 2	9.7/8”	13 K psi	7” (L)	13 K psi	9.7/8”	13 K psi
Production hole	7” (L)	13 K psi	5” (L)	13 K psi	7” (L)	13 K psi

Table 6 – Required pressure ratings wellheads

Note: a specific gas gravity of 0.11 psi/ft was applied.

In general, small sizes tubing hangers and Christmas trees are abundantly available with various contractors in various pressure ratings. It should be noted that the material design of the reservoir-fluid-wetted-surfaces should be considered. This holds for the tubing, production casing and/or liner, Christmas Tree and surface piping. As these wells could be turned into producers or injectors and then will transport great amounts of formation water, the chrome content in OCTG and the trim level of wellhead and tree should be considered.

Note that the maximum expected surface pressure for the LTG-01 well was in excess of 10,000 psi. Therefore, a 15K (15,000 psi rated) BOP stack and related pressure control equipment was required for secondary well control. Note that this is an unusual piece of equipment that is not available with the general land rig.

5.8 Recommended slim hole well design

With the sections above, it can be concluded that the ultra slim hole well design is the well that is the smallest of all and requires the least amount of rock to be drilled through. It can save on mud volumes and on cuttings transport and disposal. However, based on the fact that there is no contingency hole size available and the fact that LWD tools for the reservoir section are not be available, this design is not recommended. When the reservoir section needs to be cased-off, a solution needs to be engineered for a liner hanger with packer for a 3.1/2” string.

The slim hole design (surface liner) is neither recommended due to the need for underreaming two sections. The abrasive Chalk may require various trips in order to get that hole section opened. Apart from the additional cost of the tools and engineer, multiple trips will likely be required. Additionally 11.3/4” is an uncommon size in NL and is to be run with flush connections which are more difficult to be handled on the rig. The small clearance between the tubulars also results in high surges on the formation when running in, requiring special float equipment, and high friction pressure while attempting to wash down the casing and during the cement job.

Of the options presented in this report, the slim hole well design is the only practical option as: There is the option for a contingency hole size, the whole well can be logged in LWD, the tubulars and hole sizes are common, no underreaming is required, the reservoir section can be cored. The benefits of the ultra slim hole design do not weigh up against the benefits of the slim hole design.

This recommendation was discussed in a meeting with Jelle Wielenga EBN/Steering Committee member on the 5th of October 2017. It was decided that for the slim hole well design, a cost comparison to a full hole – LTG-01 lookalike – would be made. This is detailed in the following chapter.

6 Cost estimate and comparison against LTG-01

This chapter details the cost comparison between the selected slim hole design and the full hole design. Note that for the main services, the market was appraised for cost indications, other services come from Newell's cost inventory. The full hole well design reflects the present day drilling of LTG-01.

No commercial data of Total E&P was disclosed to Newell Engineering. This also allows for a fair comparison. Total E&P had prepared the rig site for H_2S-presence for instance, this is a service that is not included in the slim hole design or the full hole design. Also, where assumptions were made for costs, it is on the same basis for both the slim hole and the full hole.

Note that the estimates do not include for any e-line logging program. At this point in time, no actual drilling plans with geological objectives are identified. Once these plans mature, a logging program can be set up in consultation with a petro-physicist and/or an operations geologist. As there is always a need for basic formation evaluation, the following logs have been assumed to be acquired on LWD:

Hole	MWD / LWD Data acquisition programme		
Surface hole	Surface logging	MWD directional	LWD: GR
Intermediate hole 1	Surface logging	MWD directional	LWD: GR
Intermediate hole 2	Surface logging	MWD directional	LWD: GR/RES/NEUT/DENS/ PWD
Production hole	Surface logging	MWD directional	LWD: GR/RES/NEUT/DENS/ PWD

Table 7 – Assumed logging programs for slim hole well

Furthermore, the estimates provided in this chapter take no account of coring and well testing.

6.1 Time estimate

Note that a drill bit provider has analyzed the drilling times and formation rock strength measurements of the LTG-01 well and determined drilling progress with present day drill bit technology. The predicted drilling progress is an important input to the time estimate that is made for the slim hole and full hole designs.

The logging and coring time of the LTG-01 well was excluded from the data below.

The flat-line phases – tubular running phases – were taken directly from the LTG-01 well and where necessary, adjustments were made for a BOP change or the running of a liner vs. casing string.

The figure below shows the time-depth curve for the slim hole, the full hole and the LTG-01 well. It shall be noted that it is expected that using present day bit technology, a substantially higher rate of penetration (ROP) or drilling progress can be realized. The difference in ROP for the slim hole and full hole minimal, mainly caused by the difference in hole size. When a larger hole is drilled, more rock needs to be cut. A point of attention here is the logistics behind the cuttings disposal. The drilling times above are not limited by cuttings handling. For actual operations, the site and logistics need to be optimized to be able to handle high amounts of cuttings, especially in a full hole well.

Note that no time is included for waiting on weather, and the recovery of problems of the following nature; rig and third party equipment, hole stability, losses, or geological uncertainty.

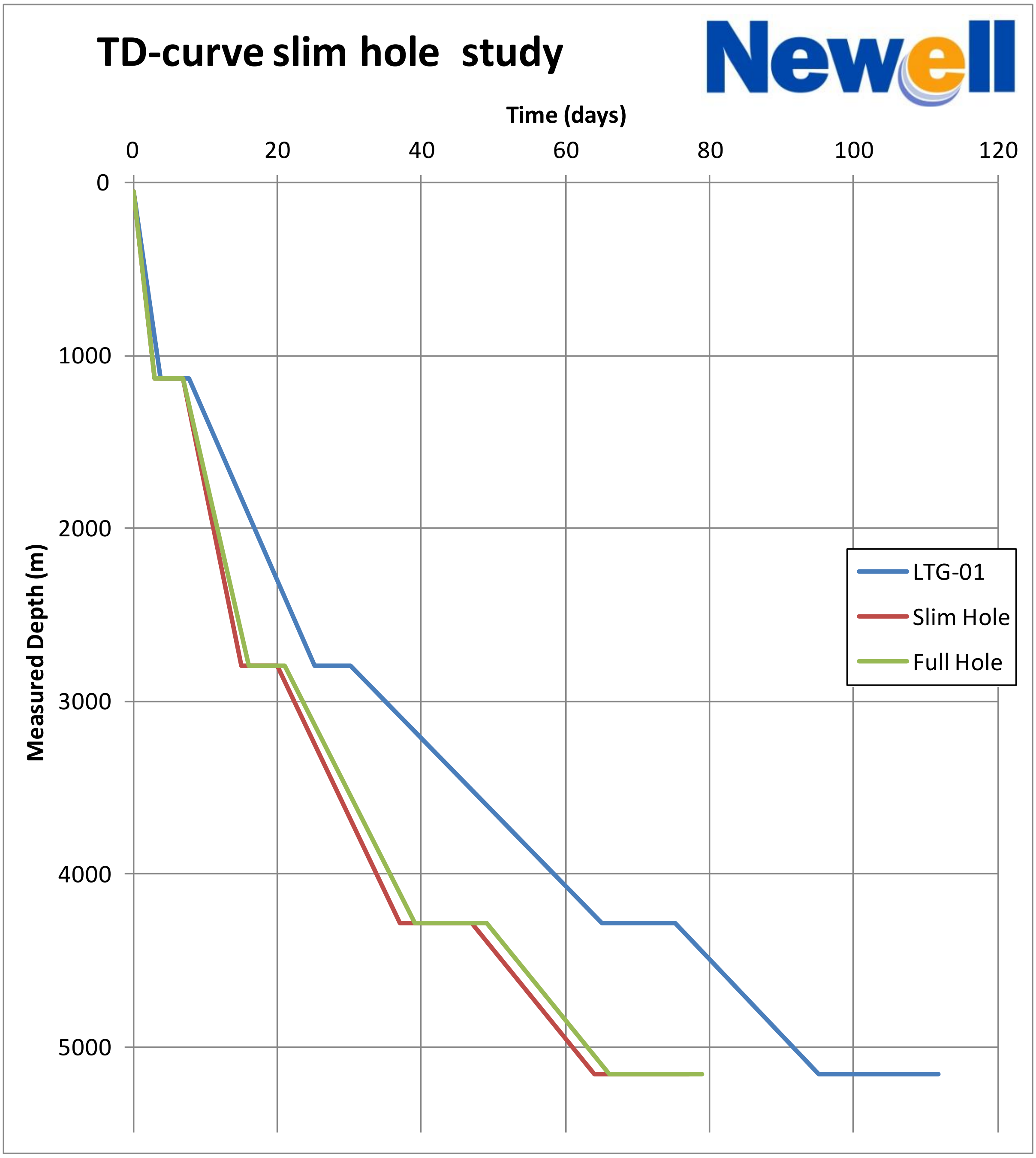

Figure 3 – Time-Depth curves LTG-01, slim hole and full hole wells

6.2 Cost estimates

Using the drilling times and the costs for various services and equipment, two estimates were realized. These are detailed in the table and the graphs below.

	COSTS SLIM HOLE	COSTS FULL HOLE
OCTG	€ 875,000.00	€ 2,147,000.00
Tubular running	€ 107,000.00	€ 120,000.00
Wellhead & tools	€ 791,000.00	€ 946,000.00
Liner hanger(s)	€ 810,000.00	€ 405,000.00
Rig	€ 2,756,000.00	€ 3,295,000.00
Operator costs	€ 1,370,000.00	€ 1,387,000.00
Rigsite	€ 830,000.00	€ 996,000.00
Cement	€ 201,000.00	€ 329,000.00
Mud	€ 676,000.00	€ 1,257,000.00
Drilling Tools	€ 807,000.00	€ 833,000.00
Drilling Bits	€ 395,000.00	€ 608,000.00
Surface logging	€ 145,000.00	€ 149,000.00
E-line logging	€ -	€ -
Solids Control	€ 747,000.00	€ 1,348,000.00
Logistics	€ 119,000.00	€ 219,000.00
Total	**€ 10,624,000.00**	**€ 14,034,000.00**

Table 8 – Cost estimates of slim hole vs full hole wells

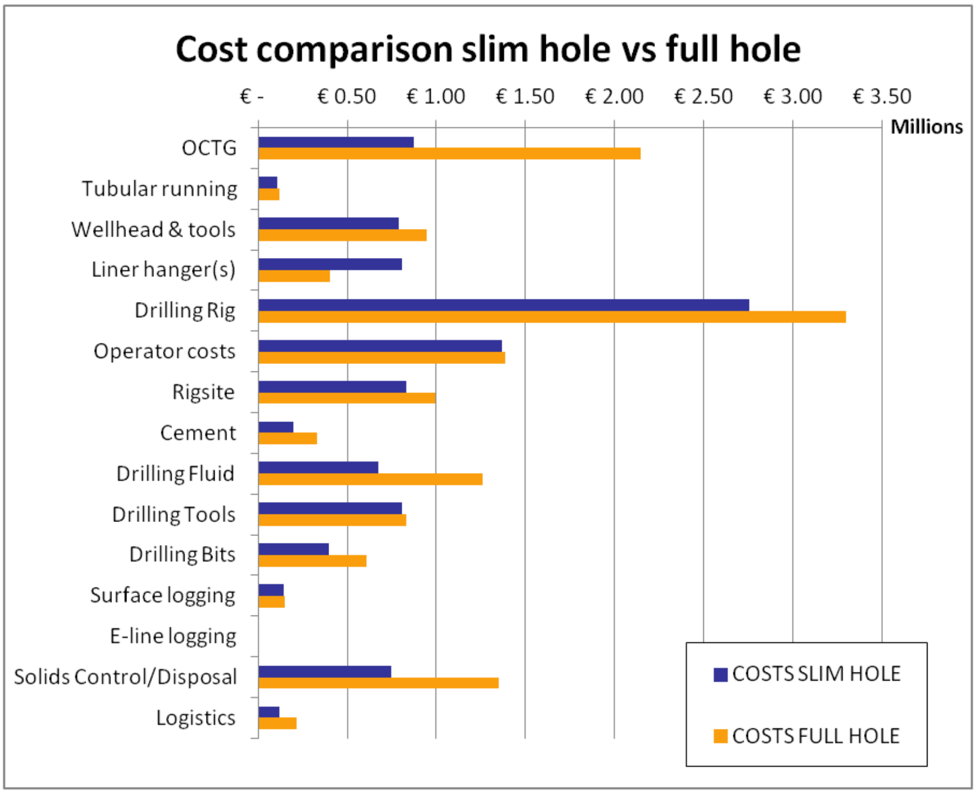

Figure 4 – Cost estimates of slim hole vs full hole wells

Note that the costs for the construction of a full hole well are 32% more than the construction of a slim hole design to reach a similar depth. The following cost categories represent a substantial difference between the two designs is:

- OCTG: Longer lengths of bigger sizes casing are required to case-off the well. This is mainly the steel tonnage price that has a high impact on this cost item.
- Liner hanger(s): The slim hole well design requires two liner hanger systems, whereas the full hole system only requires a single liner hanger. The pressure rating of both the liner hangers has to be 15k.
- Drilling Rig: The slim hole well can be drilled using a lighter rig than the full hole rig. It is assumed (but needs to be verified when a real well is designed) that a 350mT / 1500 HP rig can be contracted for drilling the slim hole well design. A 500mT / 2,000 HP rig is required for drilling the full hole well.
  A difference of 4,000 EU/day was modelled between the lighter and the heavier rig. There is also an associated cost difference in mob- and demob costs of the drilling unit.
- Rig site: A bigger and heavier land rig, requires a bigger site, one that is able to carry higher weights. The full hole well requires more fluids and bulks, again knocking on to the required space. Also, the required lay down area for casing strings and the conductor size difference is impacting the costs for the rig site construction.
- Drilling fluids: A large diameter hole results in a larger hole volume and therefore a larger active mud system. This is reflected by the difference in drilling fluids costs which are close to 85% higher for a full hole well.
- Drilling bits: The slim hole design requires smaller diameter bits that are generally cheaper than bigger equivalents.
- Solids control and disposal: The drilled cuttings that come from the well need to be collected, processed and disposed-off. The more cuttings that return from a well, the higher impact this has on costs. Especially the disposal of OBM cuttings is costly. As is evident from the table in section 4.5, the total amount of cuttings of the full hole well is more than double the amount of the slim hole well. This also has a slight impact on logistics costs.

7 Ultra Deep Slim hole drilling risks

The drilling of a slim hole well is not without risk. It must be understood that there is risk associated with drilling a smaller size well. The nature of the risk can be quite different as well as the impact. The below table provides an overview of a risk assessment that was conducted for drilling an ultra-deep slim hole well. For completeness the risks are also included for a conventional design.

No	Hazard	Consequence	Impact type	Probability	Impact	Risk
1	Drill string failure	* Due to the drilling of smaller hole sizes, smaller tools and pipe is required with lower torque limits. This may lead to drill string failures. * Fish in hole. Attempt to retrieve. * If unsuccessful, cement and sidetrack	Financial (Slimhole)	3-Moderate	4-High	MEDIUM
			Financial (Conventional)	2-Unlikely	4-High	MEDIUM
2	Drilling induced losses	* Due to smaller hole sizes, the equivalent circulation density (ECD) pressure acting on the formation while drilling, is higher. It is therefore more likely that the ECD will exceed the facture strength of the formation at a certain point. This will lead to drilling induced losses. * It can be attempted to combat these using LCM-pills, but that will not increase formation strength. Some stress caging may be attempted, but in the end, pump rate needs to be reduced leading to hole cleaning issues and the risk of not being able to reach section TD. (Ref to commit to casing prematurely hazard). * When massive losses are induced, a cement plug may need to be set from which a sidetrack needs to be initiated.	Financial (Slimhole)	3-Moderate	5-Very High	HIGH
			Financial (Conventional)	2-Unlikely	4-High	MEDIUM
3	The need to commit to a casing seat prematurely	When having to commit to a casing seat prematurely, the risk is greater than compared to a full hole well. * Losing a hole size results in the need to drill 4.1/8" reservoir section, with higher risk of drill string failure; * Unable to acquire logs; * Not achieving well objectives.	Financial (Slimhole)	3-Moderate	5-Very High	HIGH
			Financial (Conventional)	3-Moderate	3-Moderate	MEDIUM

4	Failure to maintain well control	Due to smaller hole size, less gas is required to reach critical column height for fracturing the previous casing seat. * This means that less response time is available when the well is kicking. * This result in a higher risk of an (underground) blow-out * There is less time before kick reaches surface. This is a particularly high risk when H2S is encountered.	People / Environment (Slimhole)	3-Moderate	5-Very High	HIGH
			People / Environment (Conventional)	2-Unlikely	5-Very High	MEDIUM
5	Failure to place cement as per design	Although not modelled for this well, the smaller clearances between open hole and casing do lead to higher friction pressure on the formations with the risk of fracturing the formation and inducing losses, hampering adequate cement placement. * More rig time and services will be required in order to abandon well in line with regulations.	Financial (Slimhole)	3-Moderate	4-High	MEDIUM
			Financial (Conventional)	3-Moderate	4-High	MEDIUM
6	Tool failure	In general it can be said that smaller diameter drilling tools (RSS, Motors, MWD / LWD etc.) are more sensitive. This will lead to a higher exposure when it comes to tool breakdowns. * Have to trip for new tools.	Financial (Slimhole)	4-Likely	3-Moderate	MEDIUM
			Financial (Conventional)	3-Moderate	3-Moderate	MEDIUM
7	Coring operations	When the well objective is to acquire a core, this is more troublesome in a smaller hole size due to torque limitations of the coring equipment (low torque rating on the core barrel connections). This may lead to the same drill string failure hazard as mentioned above. * In a 6” hole size, it is still possible to cut a core with 4.1/8” diameter but due to the torque limitations on the core barrel connections, only 9m cores can be cut per trip. This will result in more trips. * Note that the core in a slim hole well will be of smaller diameter which may not be in line with well objectives.	Financial (Slimhole)	2-Unlikely	4-High	MEDIUM
			Financial (Conventional)	2-Unlikely	4-High	MEDIUM

8	Future usage of well	* Note that a slim hole exploration well may have limited use as producer or injector. Compared to its full hole equivalent, the flow rates for production and/or injection may be significantly lower. The reduction can be modelled but is outside of the scope of this study.	Financial (Slimhole)	3-Moderate	5-Very High	HIGH
			Financial (Conventional)	1-Very Unlikely	5-Very high	MEDIUM

Table 9 – Risks related to slimhole drilling

Note that the risks presented in the table above represent risks associated with the slimming down of a full size well(conventional). This list does not constitute all risks when drilling for ultra deep geothermal sources. A full HAZID/ENVID session would need to be conducted on the actual design of an ultra deep geothermal well with all relevant disciplines present. One needs to consider the fact that the ultra deep subsurface is relatively unexplored leading to high geological uncertainty. Presence of hydrocarbons, H_2S, over-pressured zones is unknown. Furthermore, as temperature goes up, drilling practices need to be adjusted. High temperature fingerprinting is required when tripping pipe and sensitive flow meters need to be considered. Crew awareness needs to be raised and relevant training to increase crew’s and supervisor’s competence is a must.

8 Geothermal Exploration

In the Netherlands, drilling costs associated with exploration and reservoir assessment are a major barrier limiting the expansion and utilisation of potential geothermal reserves. The concept of slimhole exploration for geothermal projects offers the opportunity to reduce these cost significantly. However this reduction in costs needs to be carefully evaluated on a project basis.

8.1 Ultra Deep Slimhole Exploration considerations

As shown in chapter 6, slimhole exploration for ultra deep geothermal projects can provide a significant cost reduction compared to a conventional design. Operators need to consider that the risks inherent to drilling operations are already elevated, due to the fact that the intended exploration well is being drilled in mostly uncharted territory/underground. Some of these risks are further elevated when selecting a slimhole design. Well stability, well control and stuck pipe issues, but also an increased number of trips due to additional tool failures or hole problems, have the potential to quickly negate the lower costs associated with the slimhole design. The risk versus reward will need to be reviewed on a project basis and will be very dependent the already available information regarding the underground.

The well design is typically constructed from the bottom up and sized to accommodate a “contingency” casing string. As discussed in section 5.8, the recommended slimhole design is favoured over the ultraslim design due to the latter not having the option of a contingency casing string. An operator may consider not having a “contingency” string option, an acceptable risk, as “contingency” casing strings are estimated to be used in only 5% of the oil and gas exploration wells. Not having the option available may however lead to the loss of the entire well down to the point where the additional casing would have to be set. A thorough drilling risk identification may determine the highest risk to be in tophole and thus limit the cost of losing a well due to not having a ‘contingency’ casing string option. Identifying the expected trouble zones may aid the operator in making his decision.

An operator also needs to consider if the intended slimhole well can be utilised as a future producer or injector. Due to the reduced diameter a smaller submersible pump may have to be used and the increase in frictional losses and therefor lower flowrates are likely to render the well unsuitable to be used as a producer. Should it be considered to use the well as an injector, the higher required injection pressure, due to the additional frictional losses needs to be calculated and taken into account. These higher injection pressures may require a bigger surface pumping installation, increasing the operating costs and may also have a negative effect on potential for induced seismic activity. Also the fact that the increased pressure drop, due to the higher frictional losses can accelerate scaling.

The translation of the data acquired during slimhole production tests, in order to provide a prediction for the productivity of larger future production and injection wells is yet to be proven and may carry some uncertainty with it. The higher frictional losses in slimholes may limit the flow from the well and thus the extrapolation from the data to larger wellbores may not be as straightforward as one might think. More modelling and analysis by TNO may be required, to establish how to extrapolate the data acquired in slimholes.

With regards to obtaining the Dutch government financial support in the form of the SDE+, it is unclear if the 'Department of Economic Affairs' (Economische Zaken) would accept an extrapolation of productivity data obtained on a slimhole to a big bore production well. As no ultradeep geothermal wells have been drilled in the Netherlands to date and the time required to go from exploration to production will be significantly longer than on a deep geothermal project, a slimhole exploration well may have the additional benefit that it limits the expense at the front end of the project and may thereby improve the actual business case.

For the ultradeep geothermal wells no proven new technology has been identified during this study that can further reduce the cost of slimhole exploration. Furthermore these wells are likely to be high temperature and/or high pressure wells, specialist companies will have to be contracted, in both the planning and executional phase to ensure specific well integrity and well control procedures are implemented and executed. These measures are, not limited to the following: sensitive flow meters, rig and supervisory personnel training in HP/HT drilling practices, thorough subsurface studies focussed on drilling hazards, additional emergency water supplies, H2S contingency plans and equipment and involvement of local municipalities and emergency teams. High temperature tools may be required, for which cost and availability will have to be considered. Also, the selection of a slimhole design may eliminate the capability to log the well during drilling or completely eliminate the possibility to acquire the required data to evaluate the ultra deep targets.

Another consideration could be if the exploration well is intended to prove up the considered target on a project level or for an entire play or region. Should the well prove up a play, cooperation with additional stakeholders and other potential operators may be considered to share the cost of the exploration well and consider its optimum location. Obviously, by sharing the cost of an exploration well over a multitude of stakeholders the individual financial risks can be limited.

The abandonment costs of an exploration well also need to be taken into account if the selected well design renders the well unsuitable for future use as a producer or injector. It may also considered to complete the well in such a way that it can be used, for field pressure monitoring and interference testing while flowing larger wells nearby, in the later field life.

A table listing some of the advantages and disadvantages is included on the next page.

<table>
<tr><th colspan="2">Slimhole Exploration for UDG</th></tr>
<tr><th>ADVANTAGES</th><th>DISADVANTAGES</th></tr>
<tr><td>

Significant Cost reduction >30%
Lower environmental impact

- Smaller rig & smaller footprint

- Less cuttings/drilling mud

- Less flow on well test
Lower project cost at front end
Potential use as monitoring well

</td><td>

Well likely not suitable for production/injection or limited flow.
Higher total project cost (cost of additional exploration well)
Increased risk of drilling difficulties
Reduced Logging capabilities
Extrapolation of test data to largebore wells not proven
Higher injection pressures
Higher pressure drop can cause increase rate of scaling

</td></tr>
</table>

Table 10: Advantages & Disadvantages Slimhole Exploration

8.2 Deep Slimhole Exploration considerations

8.2.1 Deep Geothermal in the Netherlands

Almost all geothermal doublets that have been drilled in the Netherlands to date, have been drilled for agricultural entrepreneurs and are utilised for the heating of greenhouses. The first two doublets were drilled by Van den Bosch in Bleiswijk, respectively in 2006 and 2009. Both targeted the Rijswijk Sandstone between 1700 and 1800m TVD and the reservoir sections were drilled in an 8.½” hole size. Subsequent projects in 2011 and 2012, by Ammerlaan TGI, Haagse Aardwarmte Leyweg, Duijvestijn, Greenhouse GeoPower and Green Well Westland, were slimmed down and drilled the reservoir section in 6” or 6.1/8”hole to run 4.½” slotted liner with wire wrapped screens.

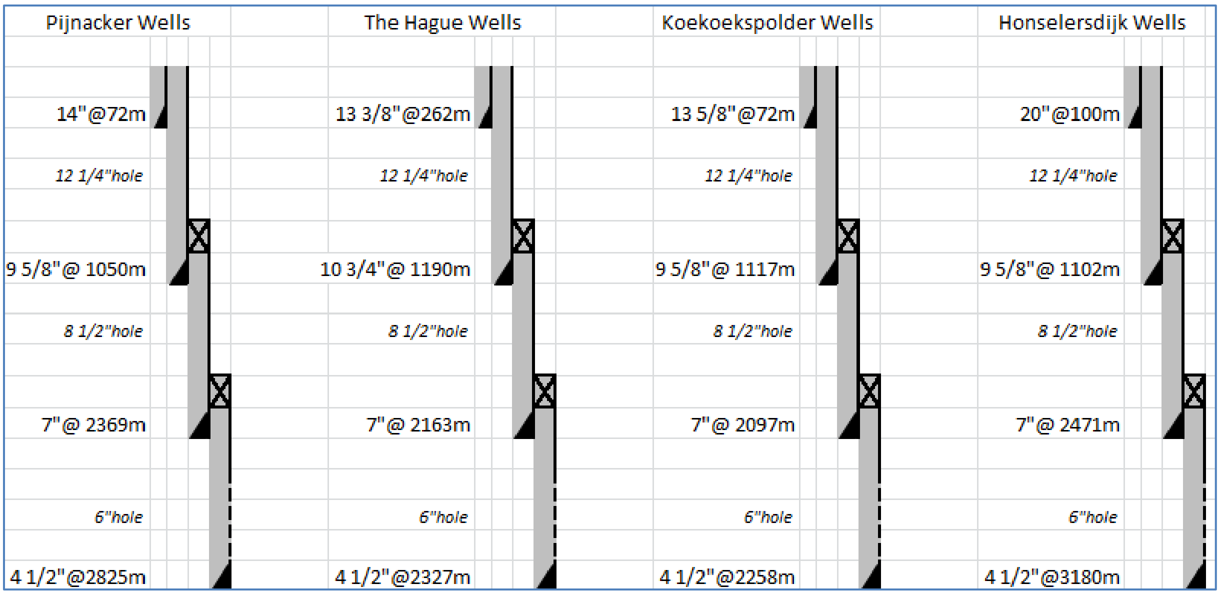

Figure 5 – Slimhole designs of existing geothermal wells in the Netherlands

From 2013, the reservoir sections in most cases were drilled in 8.½" hole size again in order to increase the achievable flowrates and thereby increase the thermal power of the installation.

8.2.2 Ultra Slim Design for Deep Geothermal exploration

When the slimhole design as applied for the deep geothermal wells would be slimmed down even further to a reservoir section in 4.1/8" diameter, a 9" slimhole wellhead system could be used to accommodate a 10".3/4"-7 5/8"- 5.1/2"casing program. This ultra slimhole well design however eliminates the possibility to utilise the well as a geothermal producer or injector due to the high frictional losses and the fact that the 7.5/8" string will have to be run to surface. As such the well would truly be drilled as an exploration well and would have to be abandoned after drilling and logging the reservoir sections.

The same considerations, advantages and disadvantages apply as listed for the ultradeep geothermal slimhole exploration wells, although the cost savings of the ultra slim design compared to the already utilised slimhole design as described above, are to be considered significantly less than the 32% calculated for the ultra-deep exploration well. An operator should have both cost models established for his project, in order to properly establish the risk versus reward balance for slimming down the well design. In this evaluation, the actual energy/heat demand for the installation should also be considered.

Appendix A – Newell Probability and Impact definition tables

RISK TABLE NEWELL ENGINEERING			IMPACT				
			Very Low	Low	Moderate	High	Very High
			1	2	3	4	5
PROBABILITY	very unlikely	1	LOW	LOW	LOW	LOW	MEDIUM
	unlikely	2	LOW	LOW	LOW	MEDIUM	MEDIUM
	moderate	3	LOW	LOW	MEDIUM	MEDIUM	HIGH
	likely	4	LOW	MEDIUM	MEDIUM	HIGH	HIGH
	very likely	5	MEDIUM	MEDIUM	HIGH	HIGH	HIGH

IMPACT TABLE				
		Financial	Environment	People
Very Low	1	Loss of more than 10k EU	Little or no known impact on ecosystem.Contained locally with no remediation required.	Negligible injury effect (FAC/MTC). Negligible health effect not affecting work or causing disability.
Low	2	Loss of more than 100k EU	Localised minimal impact on ecosystem. Any reduced environmental quality is short lived with no remedial effort required.	Minor Injury (RWC) or minor / short term reversible health effect affecting work performance.
Moderate	3	Loss of more than 1 MM EU	Uncontained or sustained release impacting on the immediate vicinity. Limited damage which is easily remediated over a short term.	Significant injury with work absence (LTI). Partial permanent disability. Significant but reversible health effects with work absence.
High	4	Loss of more than 10 MM EU	Severe lasting ecological damage to immediate vicinity. Widespread impact with major contribution to regional environmental decline. Major mitigation effort required over a period of 1 month. Potential remediation efforts required to assist natural ecological recovery.	Fatal injury. Permanent disabilities and/or irreversible health effects (<3).
Very High	5	Loss of more than 20 MM EU	Widespread and permanent ecological damage. Significant contribution to regional environmental decline. Significant remediation effort required over period > 1 month. Sustained commitment to remedial efforts for ecology and resource recovery.	Multiple fatalities. Permanent disabilities and / or irreversible health effects (>=3).

PROBABILITY TABLE		
very unlikely	1	The event may occur only in exceptional circumstances
unlikely	2	The event could occur
moderate	3	The event may occur at some time
likely	4	The event will probably occur in most circumstances
very likely	5	The event is expect to occur in most circumstances