A generic Hazard Inventory for drilling Ultra-Deep Geothermal

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Report:

A generic Hazard Inventory for drilling Ultra-Deep Geothermal Wells

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Samenvatting & Conclusies

"Alles is anders bij het boren van diepe putten"

Het boren van ultradiepe putten - met een diepte van meer dan 4.000 meter onder het oppervlak - kan niet worden vergeleken met conventionele putten. Elk deel van de put moet worden beoordeeld tegen (hoge) druk, (hoge) temperatuur, onverwachte (geologische) omstandigheden en het vermogen om te gaan met relatief onbekende omstandigheden in het boorgat. Bij het boren tot een diepte van 4.000 tot 6.000 meter onder het aardoppervlak worden putten blootgesteld aan temperaturen van ruim 200 graden Celsius. In het geval van Dinantiën carbonaatplatforms zijn deze temperaturen over het algemeen hoger dan zou worden verwacht op basis van de heersende geothermische gradiënt in Nederland (3,1 graden C/100 meter), zie Carlson (2019).

Om te helpen bij de ontwikkeling van UDG-projecten is een generiek register dreigingen aangemaakt op basis van de resultaten van een tweedaagse workshop met een team van experts uit de industrie. De potentiële dreigingen die werden geïdentificeerd zijn aanzienlijk en de effecten op specifieke projecten kunnen in potentie groot zijn. De technologische stand van de boortechniek is zodanig dat de meeste, zo niet alle, dreigingen kunnen worden beheerst.

Over de hele wereld zijn veel ultradiepe putten geboord en veel normen voor 'hoge temperatuur' en 'hoge druk' zijn beschikbaar voor referentie en gebruik bij het ontwerp en de uitvoering van de aanleg van dergelijke diepe putten. Tijdens het opstellen van dit register is rekening gehouden met gegevens en informatie van twee referentieputten van Total en NAM die in de Dinantiën carbonaten zijn geboord op meer dan 5 km diepte. Ingenieurs die bij deze twee projecten betrokken waren, hebben hun ervaring geleverd als input voor deze inventarisatie. Het toonde aan dat "alles anders is" in vergelijking met het boren van conventionele putten.

Dit betekent dat een zorgvuldige voorbereiding en planning een cruciaal onderdeel van elk UDG-project zal zijn:

'De veilige en sociaal acceptabele ontwikkeling van een UDG-project (pilot) is een randvoorwaarde.'

Elk UDG-project is uniek en moet als zodanig worden behandeld. De in deze inventaris geïdentificeerde dreigingen zullen niet noodzakelijk in alle projecten voorkomen. Daarom kunnen zowel impact- als mitigerende maatregelen per project verschillen, omdat niet elke dreiging in elke situatie op dezelfde manier moet worden behandeld. Deze technische risico-inventarisatie kan worden gebruikt om individuele projecten op risico te beoordelen en geschikte beheersmaatregelen te bepalen.

Deze technische inventarisatie van mogelijke dreigingen is een startpunt voor UDG-projecten voor het beoordelen van de mogelijke dreigingen en risico's van de individuele UDG-projecten. Het is een samenvatting van discussies die tijdens de expertsessies zijn gehouden en die per definitie niet volledig of uitputtend zijn. Mogelijk moeten ook aanvullende project-specifieke risico's worden toegevoegd. Deze inventaris moet als een levend document worden beschouwd en zal evolueren telkens wanneer nieuwe inzichten beschikbaar komen. Het wordt aanbevolen om een evaluatie uit te voeren op bijvoorbeeld een jaarlijkse basis, afhankelijk van technische ontwikkelingen en (aanvullende) kennis die is opgedaan met nieuwe(ultradiep) geothermisch projecten.

Voor deze inventarisatie is het onderwerp 'geïnduceerde seismiciteit' niet in detail besproken omdat dit reeds onderwerp is van een afzonderlijk onderzoek dat is gerapporteerd in Buijze et al. (2019).

Belangrijkste conclusies

In de afsluiting van de expertsessies herhaalden alle deelnemers de stelling dat "alles anders is bij het boren van diepe putten".

De meest voor de hand liggende risico's in diepe putten hebben te maken de gevolgen van temperatuur- en drukregimes die moet worden overwogen in elk deel van het ontwerp en de uitvoering van de put (ontwerp, materialen, gereedschappen, vloeistoffen). Hiervoor moeten steeds passende maatregelen worden genomen om schade te voorkomen.

Iets minder voor de hand liggend is de dreiging die samenhangt met het gebrek aan kennis van de diepte van de verschillende lagen. De beperkte kennis van de diepere formaties waarmee een put is ontworpen moeten worden gecontroleerd en geverifieerd terwijl de put nog in de constructiefase is. Dit betekent dat extra tijd en middelen moeten worden aangewend voor bijvoorbeeld VSP-surveys en ander soort metingen tijdens de boorfase.

Als mogelijke dreiging wordt ook het tegenkomen van giftige gassen zoals waterstofsulfide (H2S) in de Dinantiën-carbonaten genoemd. Dit kan beperkingen opleggen aan de projectlocatie in relatie tot mens en milieu én kan hoge eisen stellen aan de te gebruiken materialen, zoals stalen componenten (corrosiebestendige legeringen), boor- en meetgereedschappen en well control apparatuur.

Summary & Conclusions

"Everything is different when drilling deep wells"

Drilling ultra-deep wells - with a depth of more than 4.000 meter below surface - cannot be compared to conventional wells. Each part of the well must be assessed against (high) pressure, (high) temperature, unexpected (geological) circumstances and the ability to cope with relatively unknown downhole conditions. While drilling to depths between 4.000 and 6.000 meters below the surface the wells are exposed to temperatures well in excess of 200 degrees Centigrade. In the case of Dinantian carbonate platforms, these temperatures are generally higher than would be expected from the prevailing geothermal gradient in The Netherlands (3.1 deg C/ 100 meter), see Carlson (2019).

To assist in the development of UDG projects, a generic Hazard Register has been created, based on the outcomes of a 2-days' workshop with a team of industry experts. The hazards that have been identified are considerable and can potentially have a large impact on specific projects, but technology advances are such that most, if not all, hazards can be mitigated.

Around the world many ultra-deep wells have been drilled and many standards for 'High Temperature' and 'High Presssure' are available for reference and use in the design and execution of drilling such wells. Data and information of two reference wells of Total and NAM that have been drilled into the Dinantian carbonates at depths of more than 5 km, have been taken into account. Engineers who were involved in these two projects have provided their experience and expertise as input into this hazard inventory which proved extremely valuable. It showed that indeed "everything is different" compared to drilling conventional wells.

This means that careful preparation and planning will be a crucial part of any UDG project:

'The safe and socially acceptable development of an UDG (pilot) project is a boundary condition.'

Every UDG project is unique and should be treated as such. The hazards identified in this inventory may or may not occur in each project. Therefore, both impact and mitigating measures may differ per project because not every hazard should be treated in the same way in every situation. This technical risk inventory may be used to assess individual projects on risk and determine fit-for-purpose mitigating measures.

This technical hazard inventory is a starting point for UDG-projects for assessing the possible hazards and risks of the individual UDG projects. It is a summary of discussions that were held during the expert sessions and will by default not be complete, nor exhaustive. Also additional, project-specific, risks may need to be added. This inventory should be considered a 'living document' and will evolve each time when new insights become available. It is recommended that an evaluation is performed on, e.g., a yearly basis, depending on technical developments and (additional) knowledge gained with any new (ultradeep) geothermal project.

Please note that the subject of 'induced seismicity' is subject of a separate study, reported in Buijze et al. (2019).

Main Conclusions

Concluding the expert sessions all participants reiterated the statement that indeed *"Everything is different when drilling deep wells"*.

Stating the obvious, temperature and pressure regimes in deep wells are to be considered in every part of the well design and execution (design, materials, tools, fluids) and measures need to be taken to avoid any damage.

Perhaps less obvious, depth control can be a serious issue. With limited knowledge of the deeper formations the parameters in which a well is designed need to be checked and verified while the well is under construction. This means additional time and effort spent on VSP surveys and other types of measurements during the well construction phase.

Last but not least, the risk of encountering poisonous gasses like Hydrogen Sulfide (H_2S) in the Dinantian carbonates can pose limitations on the surface location in relation to people and environment and will require higher grade material for steel components (corrosion resisting alloys), drilling and logging tools and well control equipment.

1. Introduction

Context and reference wells

Geothermal energy systems are seen as a potential alternative for the use of fossil fuels (mainly natural gas) as the main source of heat in The Netherlands. At the time of publishing this report 22 geothermal projects are in operation and a number of projects are in development. However, the application of geothermal energy in current projects is not adequate for the provision of high-temperature heat for e.g. the process industry. It is anticipated that Ultra Deep Geothermal (UDG) energy can potentially make a substantial contribution to the transition towards a sustainable energy supply. To reach sufficiently high temperatures (>130°C) in the Netherlands, geothermal reservoirs at depths of over 4 km are required. The Dutch subsurface at these depths has not been explored extensively until now and is therefore relatively unknown. Based on the limited amount of subsurface data, the Lower Carboniferous (Dinantian) carbonates were identified by Boxem et. al. (2016) as the most promising target matching the initial requirements for UDG.

The study reported in this document is a result of SCAN, a government funded, program to scope out the potential of geothermal energy, including the Dinantian carbonates. This program includes a range of subsurface studies of the Dinantian carbonates. The results of the SCAN studies will be released and become available via www.nlog.nl and https://scanaardwarmte.nl/.

Ultra-Deep Geothermal (UDG) exploration requires the drilling of deep wells. Of the current wells that have been drilled for Geothermal exploitation applications (22 projects realized to date, totaling approximately 47 wells) only one well has been drilled beyond 4000m below surface (NLW-GT-01, total drilled depth 4021m (TVD) and plugged back). All other geothermal wells have been drilled to an average, so called ‘true vertical depth’ (TVD) of between 2.000 and 3.000 meters. This depth corresponds to an average temperature profile of around 70 to 95 degrees Celsius. Wells drilled with the objective of gas exploration or production in the Netherlands mostly fall within the depth range of 2 - 4 km. The depths mentioned are expressed as true vertical depth. Deviated deep wells (wells that are drilled under an angle) add length to the total meters drilled (this is referred to as measured depth). Below picture shows the difference between MD and TVD measurements).

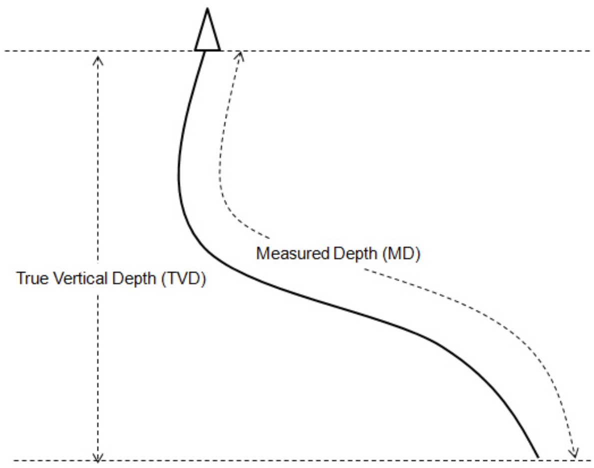

FIGURE 01: MEASURED DEPTH (OR DRILLER’S DEPTH) VS TRUE VERTICAL DEPTH

Within the UDG Exploration Work Program, ultra-deep is defined as Dinantian carbonates deeper than 4 km with associated temperatures (well) above 120 deg C. In fact, the average earth temperature below the Dutch subsurface increases with around 31-35 degrees C per kilometer. Drilling an ultra-deep well in The Netherlands is considered as a relative high-risk operation due to large - primarily geological - uncertainties and a number of rather extreme operating conditions like (high) pressure, (high) temperature or abrasive/corrosive circumstances.

EBN's database ("basisregistratie boringen") shows 44 wells onshore The Netherlands with a total depth of more than 4000m (TVDSS). Only three of these have targeted the Dinantian formation. Two of these wells have been used in this study for reference. The deepest well drilled onshore the Netherlands has been a near vertical well and reached 5994 meters TVD (6010m MD). The Winterswijk well (WSK-01) has been considered but was drilled in 1977 and thus not on par with current drilling technology. Nevertheless it would be recommended to revisit the data of this well when planning a UDG project. In Mol, Belgium, 3 geothermal wells have been drilled into the Dinantiën carbonates and data from these wells should be reviewed. These wells however have been drilled very recent and information has not yet been released into the public domain. It is unknown when this data becomes available but when it does it could prove valuable for analysis.

Hazard versus Risk

To be able to develop a UDG-project in a safe and acceptable way, it can only be undertaken if all hazards and risks involved are well understood and sufficiently mitigated or controlled.

A hazard is something that has the potential to cause harm (to people, environment, assets). Risk is the likelihood of a harm taking place and the severity of the harm when it takes place, based on exposure. **While hazards are mostly generic, the associated risks are specific**; the same hazard can result in different risk based on the exposure, applicable Risk Acceptance Criteria (RAC) and the Risk Assessment Matrix (RAM) that is used for a specific project. Mitigation of risk can again be different in various cases based on the risk perception or risk appetite (the amount of risk someone is willing to take). For this reason this study focusses on generic hazards only. The register should be used by projects to asses risk, based on the specific characteristics of the project and project organization.

FIGURE 02: HAZARD VS RISK: A SHARK IN THE OCEAN IS A HAZARD WHILE SWIMMING WITH SHARKS MAY POSE A RISK. EVEN IN THE WATER THE LIKELIHOOD OF BEING ATTACKED BY A SHARK MAY BE SMALL, BUT THE CONSEQUENCE COULD BE SEVERE.

Hazard Inventory

To identify potential hazards for deep geothermal drilling a *Hazard Inventory Workshop* of 2 days was organized with a delegation of industry experts in April 2019. Appendix A contains a list of participants. As an end-result, a (generic) technical hazard inventory or (generic) risk register was prepared that can be used by the various UDG-consortia for assessment of the individual projects.

It is recommended that all these projects prepare individual project specific Risk Inventories; this should take into account the specifics of the project, such as well location, expected depth, expected geology, expected production rates, and other (local) circumstances, e.g. (natural) surroundings, distance to neighboring activities, buildings, infrastructure, specific environments. The hazards identified and described in this report can serve as a guideline.

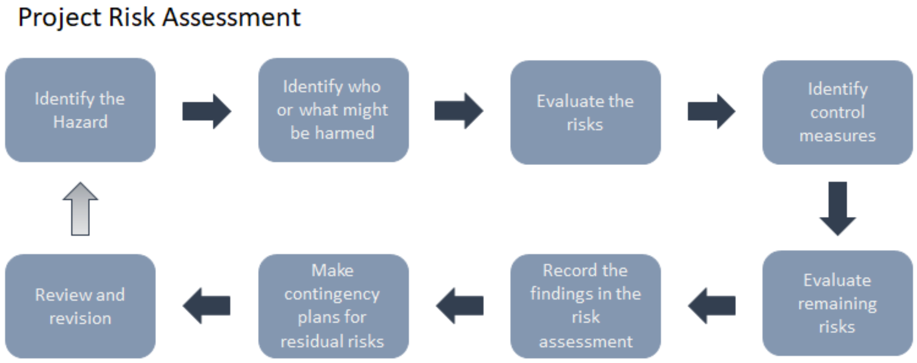

FIGURE 03 : RISK ASSESSMENT PROCESS (EXAMPLE)

2. Process

Workshop

A Workshop of 2 days to establish the UDG Hazard Inventory was organized with a selection of industry experts at the EBN premises in April 2019. The experts were selected based on their experience and expertise and discipline with regard to:

- Well Engineering
- Drilling (technology)
- Geology
- HSEQ
- System & Civil Engineering
- Completion and Well intervention & Services
- Well operations
- Drilling & Completions
- Well testing, well stimulation, well services, HTHP
- Reservoir Engineering, Production Technology
- Regulatory
- Geomechanics
- Petrophysics

The table In Appendix A lists the persons that participated in the Workshop.

During these two days a large number of topics related to UDG were discussed. To 'frame' the sessions presentations were given on the well construction process of two relevant deep wells that were drilled onshore The Netherlands (UHM-02, LTG-01). The presentations were given by the engineers that were directly involved in the planning and execution of these wells and showed the challenges the teams were faced with while drilling these deep wells.

As expected, throughout these two days it became very clear that ultra-deep drilling is not without hazards. Many factors need to be considered, mostly related to either temperature or pressure (read: the geological circumstances), or both. On the other hand, it was possible to mitigate all or nearly all of the hazards, albeit against significant costs. One of the opening remarks when asked about the difference between drilling a conventional and an ultra-deep well was: "Everything".

The DAGO Risk Assessment methodology

To align with current industry practices the methodology of risk identification was based on the '**DAGO**'[1] document 'VG Zorgsysteem' (English: the DAGO HSE management system). This HSE management system contains an extensive HazId and risk register and has been set up for conventional geothermal projects as known today[2]. The risks identified in this system can thus be classified as 'conventional' drilling risk and are as such well documented. It also forms a very useful basis for the execution of a Risk Assessment for an individual project, *without the UDG-specific risks.*

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[1] Dutch Association of Geothermal Operators (www.dago.nl)

[2] More background on this 'DAGO' Risk Assessment can be found here: https://www.kasalsenergiebron.nl/content/user_upload/Geothermal_Wells_integrity_study_report_final.pdf , in particular Appendix 5; *'Geothermal Well Integrity Study',* Woodgroup et al., October 2016.

The initial risk identification sessions concentrated on these ‘conventional’ geothermal risks and were reviewed on implications for ‘UDG-situation’ (High Temperature, High Pressure, presence of gas(ses), etc.). While drilling the so called ‘overburden’ (so: above the target formation) these issues will be comparable to the risks in conventional wells; however, the well design should take these issues (for a ‘UDG-situation’) into account when drilling the deeper part of the well.

For instance, the well will be exposed to higher temperatures and pressures and potentially gasses (like H2S) and must thus cope with the associated loads/ pressures/ chemical behavior as compared to the (original) design. In other words: the design of the well should cater for all ‘UDG-situations’, also with regard to parts that are not directly involved in drilling (and e.g. testing) the ‘Dinantian’-section.

So, as a recommendation, ***please assess carefully and follow closely all (other) drilling related hazards scenarios that are generally applicable to drilling a geothermal well.***

In particular: anticipate on effects that, e.g., high(-er) pressure and high(-er) temperatures might have on shallower formations, the use and functioning of tools, use and qualification/ selection of materials (e.g. casings), use and behaviour of fluids and cement, or any other effect.

With this important notification it was deemed not practical to revisit the existing (conventional) risk register (as used by the DAGO HSE Management methodology) and encourage the respective consortia to conduct project specific risk analyses along these lines of thought.

The HAZARD Categories (in use by DAGO):

#	Hazard
1	Hydrocarbon
2	Other Flammable Materials
3	Pressure Hazards
4	Hazards associated with differences in height
5	Dynamic situation hazards
6A	Natural Environmental hazards
6B	Induced Environmental hazards
7	Hot surfaces
8	Hot liquid
9	Eectricity
10	Electromagnetic radiation
11	Ionizing radiation
12	Asphyxiates
13	Toxic gas
14	Toxic fluid
15	Toxic solid
16	Corrosive substances
17	Biological hazards
18	Ergonomic hazards
19	Security related hazards
20	Use of natural resources
21	Noise/Light
22	Explosives

TABLE 01: OVERVIEW OF DAGO HAZARD CATEGORIES.

The ‘Deep & Hot’ part

For the so called ‘Deep & Hot’ (reservoir) sections of the well - anything between top reservoir and the total depth (TD) of the well - and in the UDG case with the main focus on the Dinantian formation, a ‘clean’ ‘DAGO’-risk inventory sheet was used, with new ‘UDG-specific’[3] categories:

1. Temperature
2. Pressure
3. Drilling & Geology
4. Well testing
5. Well stimulation
6. Permitting
7. Other UDG specific

The brainstorms during the expert sessions ultimately led to the associated identification of generic hazards and were classified along the same categories as used by the ‘DAGO’-methodology:

- Hazard Description
- Hazard Scenario
- Safeguards / Mitigation actions
- Recommendations

The results are captured in Appendix B and available as an Excel sheet, and can be downloaded from www.nlog.nl and www.scanaardwarmte.nl. In the next chapter some descriptive remarks are included to put the comments made during the session in a broader perspective.

It is noted once more that this generic UDG Hazard Inventory does not allocate the identified hazard to specific consequences, as this is - in this generic stage - not possible, without knowing more exact details on, e.g. project location, total depth, maximum expected pressures and temperatures, and contents of gasses and fluids. Such ‘scoring’ or ‘ranking’ furthermore strongly depend on the (project specific) applicable Risk Assessment Criteria (RAC) and the Risk Acceptance Matrix (RAM) that will be applied by the miscellaneous consortia. This also ensures that projects are being risked according to their own specific characteristics; each project is unique and should be assessed individually.

Note (1): Not exhaustive Hazard Inventory

This technical hazard inventory is a starting point for consortia for assessing the possible hazards and risks of the individual UDG projects. It is a summary of discussions that were held during the expert sessions and will by default not be complete, nor exhaustive. Each project will not only be assessed against the hazards/risks that are included in this inventory, also *additional, project-specific, risks need to be added*.

This inventory should be considered a ‘living document’ and will evolve each time when new insights become available. It is recommended that an evaluation is performed on, e.g., a yearly basis, depending on technical developments and (additional) knowledge gained with any new (ultradeep) geothermal project.

Note (2): Boundary condition: Location, Depth, Temperatures

During preparations of the hazard identification sessions a number of boundary conditions have been identified to somewhat ‘frame’ the assignment and give better focus to the team of experts. The UDG

[3] Note: The subject of *‘induced seismicity’* is subject of a separate study, reported in Buijze, L. et al., 2019.

Exploration Work Program specifically targets the Dinantian carbonate reservoirs which are relatively under-explored in the Netherlands. Therefore, the uncertainties in a number of important factors will be large. Reservoir depths and thicknesses vary strongly, and so will the temperatures and pressures that could be expected. In addition, the orientation and extent of fault zones vary from location to location, and so will the stress field orientation and magnitude.

The summary below indicates a wide range of parameters that can be expected, based on data from 3 wells that drilled into Dinantian carbonates in the Dutch subsurface:

Well		Top Dinantien (m)	Total (TV) Depth (m)	BHT (max)	Drilled (year)	Operator
Winterswijk-01	WSK-01	4.461	5.003	165 C	1977/1978	NAM
Uithuizermeeden-02	UHM-02	5.344	5.431	220 C	2001/2002	NAM
Luttelgeest-01	LTG-01	5.124	5.116	199 C	2004	Total

TABLE 02: BASE REFERENCES

Drilling details of 3 geothermal wells drilled into Dinantian carbonates ~4 km near Mol (Belgium) and geothermal wells drilled in the Molasse Basin in Southern Germany (e.g. ‘Holzkirchen’, with depths > 5600 m) were not available at the time of the sessions. It is recommended to include information from these wells in the future when it becomes available.

Based on the reference wells and expectations of the thermal gradient, for the hazard identification exercise it was agreed to limit this assessment to a maximum depth of 6.000 m. including the Dinantian Carbonates, and consider a maximum expected Bottom Hole Temperature (BHT) of 250 deg. C.

3. Hazards

In this part of the report a descriptive summary is given of the discussions and findings during the two days' workshop, categorized by themes.

Before any detailed engineering can be started, the purpose of the well needs to be very well defined in a basis of design document, or functional specification. The key question is: What purpose does the well have? Is the well planned to be an exploration well, or is it planned as part of a producing doublet. Will it be designed as an Injector or producer, or merely a dedicated research well?

These questions need to be answered at the earliest phase. Where in conventional geothermal well design both injector and producer wells are very similar and can in some cases be easily switched around, for UDG the type of wells will likely have to be predetermined. The answer will have a large impact on well design, planning and budget.

Note: 'The costs of a well increase disproportionately with depth and complexity' (Source: Welspec, 2016)

Well Engineering and Geology

In order to reach a good basis of **design for the well**, subsurface information is key. Surface and subsurface coordinates and any specific requirements in between determine the well trajectory and the functional specifications of a well prescribe a minimum well diameter at TD. The geomechanical formation properties as well as pressure and temperature data define the lengths of the various sections that can be safely drilled and cased and thus (including contingency scenarios) ultimately determine the diameter of the well at surface. This leads to a well design.

The well design must then be detailed and checked and adjusted for 'drillability'. Can it be done safely and efficiently, where are the risks and how can these be mitigated? Deep wells with high deviations and large outstep are challenging to drill and need thorough engineering and the right equipment and experienced people in the execution phase.

Hydraulics must be modelled and good hole cleaning practices must be followed to recover all drilled cuttings and keep the wellbore in good condition.

With long and complex well trajectories **torque and drag of drill string** and Bottom Hole Assembly (BHA) becomes increasingly important and must be modelled and referenced to during the construction phase. Drilling rig and equipment must be suitable and mitigating measures should be in place in case values exceed maximum allowable.

Depth control: in the Dutch subsurface there are large uncertainties on the depth and thickness of the Dinantian carbonates and certain other formations that will be penetrated. Therefore, an accurate well design will be very hard to achieve and additional measurements may be needed during the well construction process to validate geological models and improve depth control. Both reference wells (UHM-02 and LTG-01) have used intermediate (i.e. during drilling) VSP surveys along the well path to determine section TD to ensure a proper setting depth of the casing shoe above top reservoir.

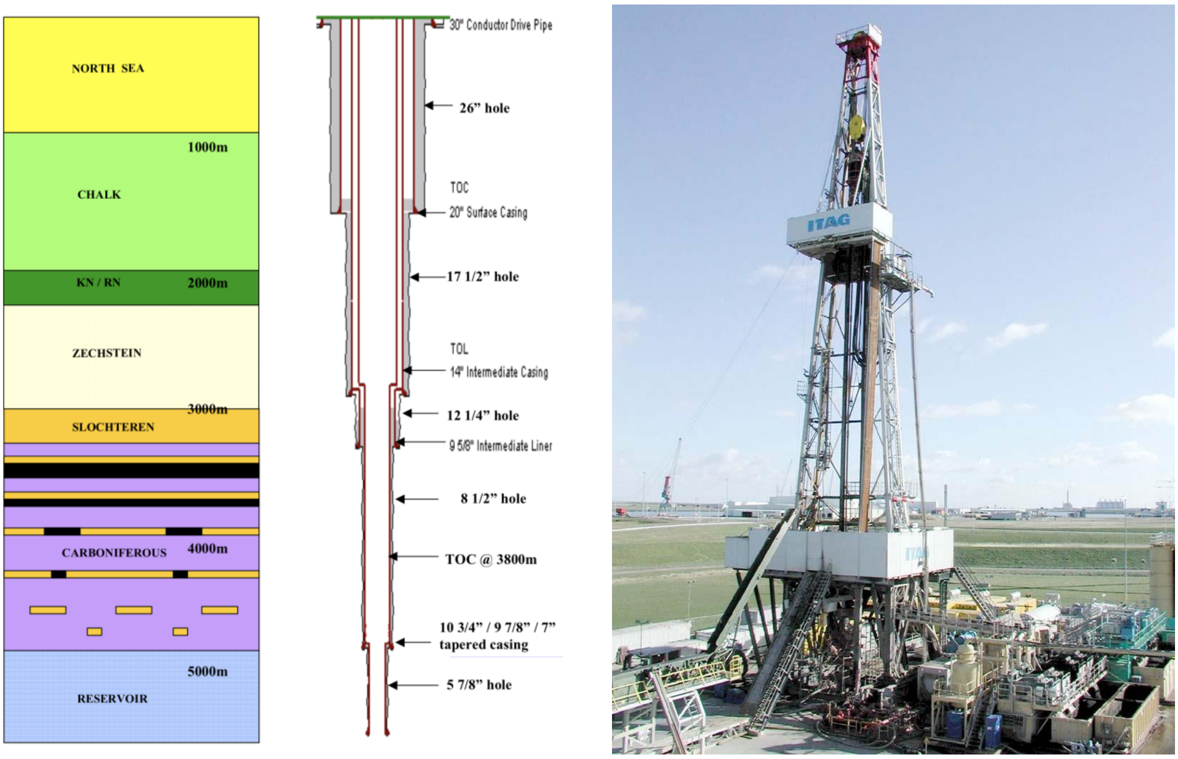

FIGURE 04: STRATIGRAPHY (LEFT), WELL DESIGN (MIDDLE) AND DRILLING RIG USED (RIGH) FOR UITHUIZERMEEDEN-02 WELL. BHT(MAX) WAS 220 °C. FROM NAM, 2001.

Accuracy and reliability of pore pressure predictions and formation strength is important for all casing shoe points and drilling fluid design and becomes increasingly difficult with deeper targets. Knowledge of pore pressure is also essential for engineering of drilling fluids as a primary well control barrier. Knowing the expected pressures provides a range for drilling fluid densities. With high uncertainties the calculated mud density can be too low or too high.

Uncertainties could be due to over-pressured zones (where in some cases pressure inclusions can occur) or under-pressured zones where due to karsts or highly fractured zones fluids can flow easily. When mud weight is too low the system is underbalanced and this can lead to an influx, or a kick, or hole stability issues. A mud weight that is too high results in an overbalance and may result in losses. This in turn can lead to an underbalanced situation in the well and loss of well control.

Pressure control is thus important for many reasons and with so many uncertainties MPD (Managed Pressure Drilling) systems may be used. These are systems commonly used in ‘HPHT’-well operations and regulate bottom hole pressure not only by mudweight, but also by applying back pressure on the entire system such that a lack of hydraulic pressure is compensated by applying varied backpressure on the system (using a choke system).

Well control equipment is designed to contain pressure in the well if primary control is lost and needs to be able to contain (more than) the highest expected pressures form the well. In conventional wells 5.000 or 10.000 psi well control equipment is sufficient, but for deep wells 15.000 psi may be needed. This can lead to considerable additional cost and specific requirements to the drilling rig that will be used to drill the wells.

The same goes for the temperature gradient. Although a general gradient is known throughout the Dutch subsurface, there are indications that through differences in conductivity of various formations the thermal gradient varies with depth and that an accurate prediction is not always possible. This can impact the selection of materials, tools, fluids and more.

In general, all loads on the well (casings and liners) need to be thoroughly defined. Temperature and pressure are the main parameters to determine, as well as fluid properties and flow. These load cases differ between the producer and injector wells and these differences are greater in deep wells than in conventional wells.

This is why it is important for the design of any well, as already highlighted above, to define a good basis of design and functional specifications for the well. The purpose of the well needs to be well defined: is the well intended to be a production well or constructed for injection of the cooled down return water? Or will the well be drilled purely for data? This will have a big impact on the final well design.

Drilling and construction of a deep well is technically challenged and needs to be well prepared. Through oil and gas exploration more and more in remote locations and to extreme depths, drilling technology has advanced and industry has developed standards and best practices for both planning, engineering and design, and execution. The following standards can be consulted for engineering, design and execution phases: NORSOK, HPHT standards & guidelines, New Zealand GT standard, ISO, API, NOGEPA, DAGO.

Location selection and preparation

The mining law and regulation as well as various environmental regulations determine largely how a **well site** should be constructed. This generally relates to the containment of anything harmful to the environment like fluid spills, but also to sound and light emissions. This also translates to specific requirements for the rig, its mud-system, hoses, seals, enclosures, ventilation and to third party vendors that supply equipment and services to the project.

For UDG exploration a few additional considerations need to be taken into account, especially for the project location in relation to **the built environment**, e.g. nearby buildings, housing, traffic etc. Geothermal exploration and exploitation differs from oil and gas considerably in that geothermal projects are always located near the point of heat demand; while oil and gas as a product can be easily transported, heat cannot. In case of urban developments, steam, containment of gasses, noise, light, smells are all factors that need to be assessed for suitability of a project location.

Part of this assessment is the **Quantitative Risk Assessment** (QRA) where the impact of uncontrolled flow of gasses (blow out, explosion) is assessed. A QRA is generally done for the potential flow of hydrocarbon gasses and in general the wellsite is large enough to contain the impact contour 10^{-6}. If H_2S (hydrogen sulfide) is expected a similar impact assessment must be made based on a potential release of H_2S and the resulting contour again projected on the proposed location. It is noted that in many of the Dinantian carbonates onshore reference wells, H_2S was present. If expected, mitigation measures must be taken to prepare and protect the rig, personnel and anyone in the near vicinity and in some cases it may lead to relocation of the drill site.

During the **test phase** of the well construction hot water is produced that at atmospheric conditions will generate much more steam than produced water from conventional geothermal wells. This steam may have an impact on the surroundings and any negative effect should be mitigated. Steam may cause visual impact like fog but may also introduce odor and precipitation that can spread outside the well location. Impact of these effects should be assessed for suitability of the planned well site.

Well construction

From surface to reservoir - drilling the overburden (conventional).

Drilling the overburden, from surface to reservoir, may be considered ‘conventional’, because most of the formations that are penetrated in that stage are relatively well known in the Netherlands. It is specifically noted that while potential issues (and mitigating measures) for these formations are known by experience, the well once cased of, must - in addition - be designed to withstand all loads exerted on it during its lifecycle. This must include deep target formation with high pressures and high temperatures and including possible corrosive fluids or gasses.

DAGO holds an HSE management system that includes a risk register. This risk register can be used as a basis to assess additional risk as a result of deeper and hotter wells and determine additional mitigating measures. (New) geothermal operators in the Netherlands are encouraged to register with DAGO and gain access to the DAGO HSE management system and use the respective extensive Risk Registers and Hazard Identifications as a basis to conduct project specific risk analyses.

The Deep & Hot part

Below a summary of some of the discussions is given as indication, it is not meant to be an exhaustive or inclusive list of hazards and reference is made to Appendix B for the full register:

Engineering, design and execution should be based on existing NORSOK, HPHT standards & guidelines, New Zealand GT standard (as well as: ISO, API, NOGEPA, DAGO).

During its lifecycle the well will be exposed to the produced (or injected) fluids and its dissolved gasses (CO_2 and H_2S), and the exposed materials should be compatible; in case of steel applicable 'NACE'**-** guidelines[4] are recommended.

Similar during its lifecycle the well may experience cyclic loading due to heating and cooling and materials will expand and shrink in various degrees. Temperature may also cause deration of the steel quality (grade). The effects of this loading should be considered in the design phase, not only on the material selection, but also on the installation, like cementing requirements.

Materials: everything that will be used in the well or for the well construction that will be exposed to high temperatures should be confirmed for compatibility. Examples are drilling tools, BOP's, seals, elastomers, liner hangers, drill pipe (connections and pipe dope). Tools may be tested under in-situ conditions (oven testing) for compatibility, although nowadays technology has advanced and temperature ratings for drilling, measuring and logging tools have improved. Any tools that are powered by downhole batteries may be affected if allowable temperatures are exceeded. Tools that are based on magnets may also be affected by elevated temperatures.

Drill pipe is selected based on requirements like strength, torque, and connections. Deep wells in particular will require high torques to transfer enough energy to the bit. With high temperatures special attention must be given to the connections and in particular the connection dope. Standard pipe dope can melt away resulting in reduced make-up torque. And if high torque is expected (very common in deep and deviated wells) specific dope should be applied to allow specific make-up torques.

Drill bits are selected for the type of formation or rock that will be drilled: type of rock or formation, hardness, required ROP. To optimize hydraulics, nozzles are inserted into the bit. These nozzles differ in composition and properties from the bit and can expand under temperature in different rates. In the past nozzles have been lost due to this effect and compatibility should be assessed.

Note: This effect should be assessed for all steel components where different steel varieties connect.

Pressure testing policies: in the engineering phase materials are selected based on engineering criteria. During installation these materials are tested for correct installation and to validate that requirements are met for safe deepening the well. This testing is based on defined load cases and follows specific design and execution standards. In some cases following specific guidelines could

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[4] National Association of Corrosion Engineers: https://www.nace.org/home .

lead to higher than allowable loads on materials. In this case specific pressure testing philosophies need to be developed to ensure integrity of the wells and give comfort to safe continuation of drilling.

The drilling fluid system (or the drilling mud) is essential in the drilling process and has many functions. It provide pressure balance against formation pressure for well control, it serves to stabilize the wellbore, transport drilled cuttings and cleans the wellbore, cool and lubricate the well bore and drilling equipment. The mud is composed of a base fluid (water or oil) and a complex of additives to meet all functional requirements and its properties need be accurately controlled. High temperature can have a large variety of adverse effects:

- the mud can lose its viscosity, causing additives to sag out of suspension.
- the mud can lose its density causing a change in bottom hole pressure and thus balance with the formation pressure.
- the mud density can change over depth and create a changing density profile over the wellbore length. To maintain control over the bottom hole pressure, and thus control over the well, this density profile must be known.
- (temperature) corrections are required to density and other property measurements.
- additives in the mud system may degrade with temperature and lose critical functionality.

The oil and gas industry has gained a lot of experience with drilling deep wells and drilling fluid engineering has advanced over the years. Fluid systems are more stable than before in high temperatures. Nevertheless, it is recommended to use mud coolers on the drilling installation to control the mud temperature.

Every section will be secured after drilling with either a casing (all the way to surface) or liner (hung off in the previous casing or liner section). The casing, or liner, will then be cemented to seal off the annular space between the casing and the surrounding formations to avoid flow. A specific cementing philosophy must be developed with cementing requirements and acceptance criteria. In high temperature conditions, casing will expand and if not well supported the casing may fail under buckling. Cement properties and recipes should thus match requirements and must be engineered to match the temperature and pressure conditions.

In execution utmost care must be taken to ensure successful cement placement. HPHT cementing expertise and procedures may be utilized.

2.2. Key Learning Points and Recommendations

- The HAZID/ risk assesment carried out at the beginning of the planning stage was essential in assessing the scope of work, and in highlighting many of the issues and risks.
- The right experience needs to be identified inside and outside your organistion, and no hesitation should be made to hire in the necessary technical expertise (i.e. we hired Geoff Thompson from Tech Spec consultants who also had very good links with Shell Expro HPHT experience).
- In non-standard wells nothing can be assumed, and unfortunately most personnal do not have the necessary experience or knowledge to give you the correct answers.
- More time and manpower should have been made available to check the drilling contractors' SMS, procedures, HSE documentation, etc. NAM should have assisted with manpower and expertise at an early stage; instead of allowing a Shell-led audit team to comment on the same shortly after operations began.

FIGURE 05: SOME OF THE KEY LEARNING POINTS AND RECOMMENDATIONS OF WELL UITHUIZERMEEDEN-02. FROM NAM, 2001.

4. References

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- Standards:
  - NORSOK standards: https://www.standard.no/pagefiles/1315/d-010r3.pdf
  - https://www.standard.no/pagefiles/1315/d-010r3.pdf
  - New Zealand Standard: Code of Practice for deep geothermal wells: NZS 2403:2015, https://shop.standards.govt.nz//catalog/2403%3A2015%28NZS%29/view
  - API
  - DAGO.nu
  - NOGEPA

Appendix A: List of participants.

List of individuals that participated in the Workshop sessions in April 2019.

NAME	COMPANY
D. Drenth	Independent Chairman
W. Teertstra	Independent Scribe (via EBN)
J. Wielenga	Lloyd's Register
H. Wierenga	Vanguard
L.J. Ursem	Geothermie Partners
W. Botermans	Geothermie Partners
V. De Ruiter	Well Engineering Partners
R.J. Lodder	NAM
P. Hopmans	TNO
K. van de Valk	TNO
B. Jaarsma	EBN
M. Middelburg	EBN
I. de Vos	EBN
M. Mozafari	EBN
J. Drenth	EBN
R. Wijnhoud	-
J. Hunia	-
D. Verbiest	DAGO
J. van der Sijp	SodM
E. Schrijver	SodM

NOTE: NOT ALL PEOPLE ATTENDED FOR THE FULL 2 DAYS.

Appendix B: Hazard Identification inventory

The inventory sheet is also available as an Excel file on www.nlog.nl and www.scanaardwarmte.nl

Hazard Number	Hazard Description	Scenario		Safeguards / Mitigation	RECOMMENDATIONS Action	Who	By
0	**UDG SPECIFIC HAZARDS**		**NOTE: THIS RISK REGISTER IS MEANT FOR GENERIC USE ONLY.**	**NOTE: THIS RISK REGISTER IS TO BE CRITICALLY EVALUATED FOR EACH INDIVIDUAL PROJECT.**	**NOTE: THIS RISK REGISTER IS MEANT FOR GENERIC USE ONLY.**		
0.0	***GENERIC GEOTHERMAL WELL***		***Please assess carefully and follow closely all (other) drilling related Hazards scenarios that are generally applicable to drilling a geothermal well.***	***Reference is made to, e.g., the 'DAGO' (generic) HAZID-template for geothermal projects, or any other useable reference.***	***Please assess carefully and follow closely all (other) drilling related Hazards and scenarios that are generally applicable to drilling a geothermal well. ANTICIPATE ON EFFECTS THAT, e.g., HIGH(-ER) PRESSURE AND HIGH(-ER) TEMPERATURES MIGHT HAVE ON SHALLOWER FORMATIONS, THE USE AND FUNCTIONING OF TOOLS, USE AND QUALIFICATION OF MATERIALS (e.g.***		
0.1	**TEMPERATURE (UDG-specific)**						
	High(er) temperatures due to nature of UDG ('Ultra Deep').	0.1.1	Encounter high temperatures (as per objectives), temperature gradient can be higher/lower than expected. ***Note: final Temperature range/ Temperature gradient can be much higher (a number of Dinantien reference wells show significantly higher gradient), leading to misc. negative effects (than in drilling a 'normal' well, see below).***	International industry standards on High Temperature (and High Pressure, ref. below) wells (e.g. NORSOK, HPHT standards & guidelines, New Zealand GT standard, ISO, API, NOGEPA).	Assess and incorporate applicable industry standards in planning and execution phases. Define worst case scenarios and mitigations.		
	Temperature effects on materials (casing, drilling equipment, fluids).	0.1.2	Deterioration of materials and equipment such as casing, liners, liner hangers, drilling tools (bits, mudmotors, M/LWD tools, etc), well control equipment, seals, drilling fluids and additives, cement. ***Note: also temperature effects on higher/ un-deeper trajectories!***	Suitability of all components in well construction process anticipating worst case temperature effects. Consider using mudcoolers, extra mudcirculation, etc. Use field proven technology, concider simple/mechanical tools vs hydraulic and electronic components. For liner hangers consider mechanical setting mechanisms versus hydraulic tools, multi trip versus single trip systems.	Asses and incorporate proper material and equipment selection during engineering and execution phases. Develop and implement an efficiënt QA/QC system. Consider pre-testing critical parts and components under downhole conditions. Note: check compatibility of materials, drillpipe conections (including make up torque and suitable pipe dope), (ring) gaskets, seals, bearings, etc.		
		0.1.3	Effect on material bahaviour, in particular metals: higher temperatures will lead to elongation ('uitzetten')	See above. In particular be aware of 'well growth'.	See above.		
		0.1.4	Effect on (selection of) measurement and logging tools (sensitive equipment).	Suitability of all components in well construction process due to worst case temperature effects. Consider using mudcoolers, extra mudcirculation, etc. to reduce temperature. Use field proven technology, concider simple/mechanical tools vs hydraulic and electronic components. Only wireline logging and LWD/MWD contractors with High Temperature capabilities should be invited and selected.	See above. Only wireline logging and LWD/MWD contractors with High Temperature capabilities should be invited and selected		
		0.1.5	Temperature impact battery performance and batterylife of MDW-equipment and other electrical devices.	Compatibility of batteries vs. temperature and use only fit-for-purpose equipment. Only wireline logging and LWD/MWD contractors with High Temperature capabilities should be invited and selected	See above.		
		0.1.6	Temperature impact on magnet performance and strength. Magnets are sometimes used in fishing equipment.	Compatibility of magnets vs. temperature and use only fit-for-purpose equipment.	See above.		
	Temperature effects on humans and environment.	0.1.7	Various effects due to hot surfaces on surface equipment (Note: higher than conventional wells), steam generation (mist, vapours), visual effects outside wellsite, breathing of vapours.	Proper personal protection equipment ('PPE') for personnel, wellsite preparation, anticipate effects to environment and neighbouring surroundings of wellsite. Dedicated temperature measurment devices on critical locations. Develop correct procedures.	Assess and incorporate correct procedures to safeguard personal protection, supply PPE means to all involved.		
		0.1.8	High temperatures may lead to changing of the density-profile over the well. Mudweight at surface may not be representative of mudweight downhole. ***NOTE: Density deviations may lead to well control incidents.***	Accurate knowledge and selection of drilling fluids type and properties under actual/expected conditions. Extensively test drilling fluids under actual downhole conditions. Develop correct procedures, e.g. assess circulation time to condition mud (may take several hours (>5 hrs, depending on bottoms-up time). Reduce Rate of Penetration (ROP), temperature	Design and execute extensive mudtesting in close cooperation with mud service company. Incorporate and adhere to correct procedures.		
		0.1.9	High temperatures may lead to changing viscosity/yield point, sagging of weighting material, degradation of mud additives, other effects.	Accurate knowledge and selection of drilling fluids type and properties under actual/expected conditions. Extensively test drilling fluids under actual downhole conditions. Develop correct procedures, e.g. assess circulation time to condition mud (may take several hours (>5 hrs, depending on bottoms-up time). Reduce Rate of Penetration (ROP), temperature	See above.		
	Temperature effect on cement.	0.1.10	High temperature may effect cement quality. Cement placement is critical for longevity of well: e.g. expansion of gas or fluids in pockets (inclusions) may lead	Accurate knowledge and selection of cementing requirements and criteria, cement type properties and cementing procedures under actual/expected conditions. Extensively test cements, including washers/ spacers under actual downhole condition.	Extensively test cement composition under actual downhole conditions in close cooperation with cementing service company. Develop correct procedures (including top of cement, hole cleaning, spacers,		

0.2	**PRESSURE (UDG-specific)**						
	High(er) pressures due to nature of UDG ('Ultra Deep').	0.2.1	Encounter high pressures in formations (or higher than expected) due to depth and/or abnormalities in formations or due to fractures/ faults. ***NOTE: (unexpected) pressure behaviour may lead to well control incidents.***	International industry standards (e.g. NORSOK, HPHT standards & guidelines, New Zealand GT standard, ISO, API, NOGEPA).	Incorporate applicable industry standards in planning and execution phases. Define worst case scenarios and mitigations. Assess potential overpressures due to pressure inclusions.		
		0.2.2		Fit-for-purpose' well control philosophy and select associated well control measures/equipment. Critically assess requirements for BOP's, downhole pressure management, APWD (Annular Pressure Measurements While Drilling) for realtime pressure control, ECD (Equivalent Circulating Density), MPD (Managed Pressure Drilling), UBD (Underbalanced Drilling), other.	Study pressure regimes, pressure and fracture gradients offset wells. Incorporate selected well control philosophy and well control measures/equipment. Include (longer) order times ('long lead items') in planning. Execute Driiling-Well-On-Paper ('DWOP') exercises. Perform 'test-drills' to be able to react swiftly with whole drilling team on abnormal situation(s).		
		0.2.3	Uncertainties of pressure ranges leading to incorrect pore pressure prediction in HPHT wells.	Assume large variations in actual pressures (both higher and lower) during drilling, develop contingency scenarios & mitigations and define equipment requirements for fast response.	Study pressure regimes, pressure and fracture gradients offset wells. Incorporate selected well control philosophy and well control measures/equipment.		
		0.2.4	Influx may occur due to higher than expected formation pressures, or loss of balance.	Availabilty of systems and equipment such as: Gas detection sytems, Early kick detection (HPHT procedure), including software to model fingerprint, accurate pitlevel monitoring. Mudlogging program, Early warning sysytem (Note: the 'D-exponent' does not work in carbonates, need shale layers (above	Develop and apply suitable procedures for influx and well control scenarios. Execute HAZOP of all well control system and mudsystem/components. Perform 'test-drills' to be able to react swiftly with whole drilling team on abnormal situation(s).		
		0.2.5	Losses may occur due to lower than expected formation pressures, fractured or karstified zones.	Close monitoring and accurate monitoring equipment, lossed circulation scenario planning (including mitigation scenarios), LCM strategy (LCM,	Develop and apply suitable procedures for lost circulation. Perform 'test-drills' to be able to react swiftly with whole drilling team on		

0.3	DRILLING & GEOLOGY (UDG-specific)						
	Formation strength uncertainty.	0.3.1	Uncertainties of formation strengths can lead to inadequate well design (e.g. shoe placement, gas filled well).	Design standards for exploration drilling/ characteristics (i.e: 'unknown teritory'). Plan for (setting) additional casing string(s) (for e.g. well control). Develop formation strength testing requirements and strategy.	Study pressure regimes, pressure and fracture gradients offset wells. Incorporate selected well control philosophy and well control measures/equipment. Plan for formation strength Inflow Test/FIT, Leak-off Test/LOT.		
	Integrity testing, pressure testing of well.	0.3.2	FIT/LOT/LIT difficult to obtain desired values. Procedures for FIT/LOT's at large depths: difficult to execute, difficult to interpret.	Procedures and HPHT expertise.	Design, incorporate and adhere to best suited testing procedures.		
	Integrity testing of barriers.	0.3.3	Integrity testing of barriers (pressure testing for barrier verification) difficult or impractical (may exceed limits).	Barrier verification philosohy (e.g. inflow testing (Horner test) instead of pressure testing).	See above.		
	Presence and release of H2S.	0.3.4	Release of H2S can lead to asphyxiation and death ***NOTE: Dinantian carbonate have known H2S potential. Note: QRA-contours are expected to extend (well beyond) the***	H2S assesment, H2S detection (Gastrain (gas garret)), training to personnel (incl. PPE such as escape masks, pressurized air), drilling fluidproperties to buffer H2S in the mud (scavenger) PH-control.	Execute QRA for potential release of H2S. Incorporate and adhere to correct procedures. Perform 'test-drills' to be able to react swiftly with whole drilling team on abnormal situation(s).		
		0.3.5	H2S is highly corrosive to steel.	H2S resistant materials in well design and contruction (casing and liners, seals, BOP's), surface equipment.	Addres potential presence of H2S in welldesign; if H2S present all materials need to be suitable for sour service (apply NACE (National Association of Corrosion Engineers) classification for steel.		
	Depth control inaccuracy (leading to encountering horizons at other levels than expected).	0.3.6	Formations can come in shallower or deeper and can lead to wrong mudweight. This has direct implication on wellcontrol and well design.	Continuous monitoring of formations, through mudlogging and M/LWD. Plan for contingency casings for wel control. Deploy VSP survey(s) to validate or update depthmodel. Close interaction between well operations and G&G staff. Plan for swift action on mudweight, pressure prediction, ECD control, MPD systems.	Include (variations in depth) into final well design (and scenarios) and associated drilling and evaluation procedures.		
		0.3.7	Formations can come in shallower or deeper and can lead to wrong placement of casing (shoe). This has direct implication on wellcontrol and well design.	Continuous monitoring of formations, through mudlogging and MWD/LWD. Plan for contingency casings for wel control. Use VSP survey(s) to validate or update depthmodel. Close interaction between well operations and G&G staff.	See above.		
		0.3.8	Target formation Dinantian shallower than expected.	Continuous monitoring of formations, through mudlogging and MWD/LWD. Use VSP survey(s) to validate or update depthmodel. Close interaction between well operations and Geofysical and	See above.		
		0.3.9	Target formation Dinantian deeper than expected.	See above. Be prepared to drill deeper. Have sufficient materials in stock.	See above.		
		0.3.10	Cuttings description hampered due to too fine cuttings: cuttings are milled and ground to very fine fraction and can get mixed up due to long well trajectory.	Alternative measurements and intermedient logging to keep track of gelogical situation in well in close interaction between well operations and G&G staff.	Implement strict geological tracking methodology in close interaction with geological support services/ on-site geologists.		
		0.3.11	Thickness of Dinantien (reservoir) more than expected.	Be prepared for deeper drilling, or stop sooner if economics of project allow. Have sufficient materials in stock in case of deeper drilling).	Prepare decision-tree on how to decide when well targets have, or have not, been achieved, and include scenarios.		
		0.3.12	Thickness of Dinantien (reservoir) less than expected (less productive zone).	Review options to encounter more target formation (e.g. increase angle ('horizontal'), well stimulation techniques,....). Might need sidtrack of original well, extra materials, langer duration, (significant) extra costs	See above.		
	Drilling problems to, near or in Dinantien.	0.3.13	Devonian formation below Dinantien could be charged, leading to influx	Pore pressure prediction and depth control. Be prepared for higher than expected pressures,	See part 0.1 in this Risk Register on 'Pressure'		
		0.3.14	Drilling into fault zone may lead to higher than expected pressures; fault may be connected to other formation/pressure regime.	Good seismic mapping of faults, welltrajectory planning, be prepared for losses and/or influx. Wellcontrol measures. Pore pressure prediction and depth control. Be prepared for higher than expected pressures.	See part 0.1 in this Risk Register on 'Pressure'		
		0.3.15	Drilling into fault zone, may lead to losses.	As above.	See part 0.1 in this Risk Register on 'Pressure'		
		0.3.17	Drilling into fault zone may lead to borehole (in)stability issues (collapse, caving, stuck pipe).	Good drilling practices, drilling fluid engineering and maintaining of drilling fluid properties. Monitoring of parameters. Stuck pipe prevention training. Borehole stability studies (Geomechanics), stress caging techniques.	Design for and adhere to best drilling practices. Define worst case scenarios and mitigations.		
		0.3.18	Long well trajectories may lead to high torque and drag, which can harm drilling equipment or prevent well to be finished.	In engineering phase well trajectory optimisation for torque and drag through simulation. Design welltrajectory and drilling equipment (rig, drillstring, stabilisers, torque reducers, etc.) to minimise torque and drag. In drilling phase monitor torque and drag, follow trends and compare to simulation results. Take additional measures if needed (e.g. mud additives).	See above. In well design phase: execute torque&drag simulation and welltrajectory optimisation. In drilling phase: closly monitor torque&drag bahaviour.		
	Coring in deep wells needs special expertise.	0.3.19	Trapped pressure in core barrel.	Follow best coring practices. : Pressure release at shallow levels, the last couple of 100 m and shallower is important. (This is typically implemented at stopping at 200 m, 100 m, 50 m and 25 m for 30 min-1 hr to release the trapped pressure in the core. Do not have deeper stations than approximately 200 m, as these do not really add to the risk reduction.)	Design, incorporate and adhere to coring equipment and procedures in close corporation with coring service company.		
		0.3.20	Gas expansion in cores.	Follow best coring practices, control pulling-out speed.	Same.		
	Logging in deep wells needs special expertise.	0.3.21	Trapped pressure in logging equipment (applies to fluid sampling tools and sidewall coring tools).	Follow best logging practices.	Design, incorporate and adhere to logging equipment and procedures in close corporation with logging service company.		

0.4	**WELLTESTING (UDG-specific)**						
	Well testing at high temperature.	0.4.1	Temperature impact on well testing equipment and other devices (e.g. perforating guns).	Compatibility of well testing equipment, use only fit-for-purpose equipment.	Design, incorporate and adhere to well stimulation equipment and procedures in close corporation with well stimulation		
	Blockages of piping, valves, equipment due to scaling.	0.4.2	Handling of salt saturated fluids on surface, cooling may lead precipitation of salts/other solids (scaling in coolers).	Anticipate effects of salt precipitation in surface equipment, continuous cleanup, availibility of backup or auxiliary equipment.	Design and select equipment and procedures, including NORM.		
	Hot surfaces, liquids (brine) and gasses (steam) may pose risk to personnel.	0.4.3	Generation of steam/ vapours from welltest outlet and production storage basins may lead to personal injury,	All areas with hot fluids, steam barriered off (no-go areas); personnel to keep clear of risk areas.	Assess and incorporate correct procedures to safeguard personal protection, supply PPE means to all involved.		
	Hot surfaces, liquids (brine) and gasses (steam) may pose risk to outside perimeter.	0.4.4	Generation of steam/ vapours from welltest outlet and production storage basins may lead to visibility restraints	Plan welltest in conjunction with weather conditions, warn surrounding neighbours. Plan to limit disturbances.	Investigate mitigation actions, engage stakeholders.		
	Transport and temporary storage of (hot) well test fluids.	0.4.5	Well test fluids need safe temorary storage facilities when flowing from well test equipment, requiring seperate surface area and/or trucking of fluids to other storage area. Due to high temperature of fluids, this is more complex than conventional geothermal	Availability of sufficient well testing fluids storage space, either on drilling location or in vicinity (e.g. trucking or piping).	Anticipate on well testing when designing well location (and lay-out thereof), or have alternative at hand (e.g. trucking or temporary pipeline). Ensure proper environmental protection and procedure(s) is in place (e.g. to prevent leakage, clean-up). Also here, effects to reduce steam generation is of importance		
0.5	**WELL STIMULATION (UDG-specific)**						
	High pressure stimulation (if 'standard' well testing does not give expected results). ***NOTE: High pressure stimulation may require significant efforts (incl.***	0.5.1	Very low or no positive results from (conventional) well testing process.	Application of well stimulation techniques. Have sufficient equipment and materials on call-off.	Be prepared to apply well stimulation techniques. Prepare decision-tree on how to decide when well stimulation is required, and with which technology (incl. duration, intensity, lenghts, etc.).		
		0.5.2	Activating fault(s) leading to local seismic activities leading to potential (local) damages and/or public	Proper engineering of well stimulation plan. Installation of seismometers, Seismic Risk Action plan.	Design, incorporate and adhere to well stimulation equipment and procedures in close corporation with well stimulation		
0.6	**PERMITTING (UDG-specific)**						
	No or late permit(s) issued by official authorities.	0.6.1	Delay due to waiting on permit(s), or no permit(s). E.g. longer than expected Environmental Impact Assessment(EIA/'MER') procedure. ***Note: multiple official authorities ('Bevoegde Gezagen') are invoved in submitting permits based on legal obligations (i.e. Ministries, Province, Local Government***	Follow correct permitting applications and associated preparations (such as an EIA/MER), once location is known. Due to specific nature of the UDG-project ('new'), anticipate on more (rigid) preparations, multiple information sessions, but also court-procedures up to Council of State/ 'Raad van State'. ***Note: Ministry of Economic Affairs (as official authority under the Dutch Mining Act) to***	Study required permitting applications and associated preparations (such as an EIA/'MER'), once location is known and follow-up as soon as possible. Involve Ministry of Economic Affairs, and other official authorities, at earliest moment. Initiate communication strategy.		
		0.6.2	Delay due to additional queries by authorities or, e.g. State Supervision of Mines (SSM). Focus by SSM is onto geothermal sector as a whole, for UDG in particular. **Note: SSM is executing its own Risk Assessment related to UDG (2018/2019).**	Very thorough well engineering process anticipating worst case temperature and pressure effects. Traceable QA/QC process. Regular contact and updares to relevant authorities. Assess findings of SSM Risk Assessment into UDG (expected Q3 2019).	Follow best engineering practices and detailed preparations and internal cross-checks. Develop and implement international based QA/QC system(s) (e.g. ISO 9000, 14000, 45000). Inform all stakeholders on regular basis. Avoid miscommunication. Incorporate findings of SSM UDG Risk Assessment into		
		0.6.3	H2S and QRA contours could be much larger in diameter than an 'standard' well.	Alternative location. Execute 'quick-scan' on external effects (so outside drilling location), once location is known. This might lead to a change in location selection.	Execute 'quick-scan' on external effects (so outside drilling location), once location is known, prior to starting up formal permitting process. Have alternative location(s) available.		
0.7	**OTHER UDG-SPECIFIC**						
	UDG-specific Seismic phase (if needed).	*0.7*	*NOT ASSESSED.*	*NOT ASSESSED.*	*NOT ASSESSED.*		
	UDG-specific Production phase (in close conjunction with	*0.7*	*NOT ASSESSED.*	*NOT ASSESSED.*	*NOT ASSESSED.*		
	UDG-specific Injection phase (in close conjunction with	*0.7*	*NOT ASSESSED.*	*NOT ASSESSED.*	*NOT ASSESSED.*		
	UDG-specific Monitoring phase (during life-time of wells).	*0.7*	*NOT ASSESSED.*	*NOT ASSESSED.*	*NOT ASSESSED.*		
	UDG-specific Welll Maintenenance/ Intervention phase (e.g. after 5-10-20-30 years, or in case of unforseen situations).	*0.7*	*NOT ASSESSED.*	*NOT ASSESSED.*	*NOT ASSESSED.*		
	UDG-specific Abandonment phase.	*0.7*	*NOT ASSESSED.*	*NOT ASSESSED.*	*NOT ASSESSED.*		
	UDG-specific (external) Communication.	*0.7*	*NOT ASSESSED.*	*NOT ASSESSED.*	*NOT ASSESSED.*		
	UDG-specific Financial/ Economical considerations.	*0.7*	*NOT ASSESSED.*	*NOT ASSESSED.*	*NOT ASSESSED.*		

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