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D1.5 Geo-Drill KPIs

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REVISION HISTORY

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[1] Dissemination level security:

PU – Public (e.g. on website, for publication etc.) / **PP** – Restricted to other programme participants (incl. Commission services) /

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GEODRILL

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Document: D1.5 Geo-Drill KPIs

Version: **01**

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1. EXECUTIVE SUMMARY

This deliverable provides a report on the review of key performance indicators (KPIs) related to hammer and drill components including identification of success criterion for material and coating synthesis. This is a *working* document, and, in its *first* version, provides a distinctive starting point for the consortium and an initial direction for concentrating the focus on benchmarking the success criterion for materials and coating synthesis and optimisation, development of drill components including testing and validation. The document also outlines the methodology followed to identify the KPIs according to the objectives defined including the limitations, as foreseen, due to several unknown variables (as described further in the document) at this early stage.

The document should be read in conjunction with D1.4 Finalised sensor and analysis specification, where KPIs for the data acquisition system has been specified.

2. INTRODUCTION

The project Geo-Drill aims to develop "holistic" drilling technologies that have the potential to reduce the cost of drilling to large depths of 5km or more and at temperatures as high as 250°C by:

- Assessing the current technologies, their weaknesses and strengths and subsequent improvements.
- Developing a new "mud hammer" system that can cope with strong formations and elevated temperatures.
- Developing surface coatings that extend componentry life through the improvement of their erosion and wear resistances.
- Developing new substrate materials that are more robust and less affected by down hole stresses.
- Developing new tool joint materials and possibly tool joints, that prolong drill string componentry life-cycles and reduce pressure losses due to internal friction.
- Developing new sensors that can be installed throughout the drill string to gather data, to allow for optimisation of the drilling process.
- Developing new technologies that permit data to be transmitted to the surface in "real-time", helping mitigate against formation and equipment problems, before they occur.
- Integrating with existing surface equipment, to avoid wholesale changes to the drilling process.
- Ensuring that the technologies/processes are suited to real-world environments, easily accessible, cost-effective and represent a major step forward in reducing exploration and production drilling costs.

Establishing KPIs help measure relative progress and it is important to understand, that they are just indicators (or snapshots) of where things are at any point in time. As each KPI is achieved, a new one should be set and where an activity falls short, it should not be seen as a failure, but as a need to review and assess. This is of particular relevance to deep drilling, as no two wells are the same and geology can, at best, be unpredictable. Well (drilling) planning is very important, but so is the capability to adapt, to make sure the drilling process is fully optimised. This approach needs to be incorporated into the Geo-Drill project, as one thing changes, this may very well affect something else in the process. Certainly, the new hammer will overcome many of the problems facing air/water hammers, but it will probably generate new challenges especially around the selection of drilling fluids and the rate of removal of cuttings from the wellbore. The downhole sensors will provide real-time information of downhole conditions; this will significantly change how hard rock wells are drilled, through the ability to constantly optimise all parameters at the control of the surface team and their systems. As such, combination of development of these new technologies with existing in-hole drilling equipment is quite challenging and necessitates identification and a continuous review of the project Key Performance Indicators (KPIs). However, as deep geothermal drilling is still in a fledgling stage of development, as most active plants are from steam-field generation sources, setting KPIs and SMART (specific, measurable, achievable, relevant, time-bound) objectives can potentially be quite challenging.

The project itself has a number of points outside of its control:

- Sub-surface geological conditions.
- Site location(s) – environmental controls.
- Well profiles – diameters, casing depths, vertical or radiused.
- The need to drill some sections with standard drilling technology.
- Rig availability/suitability.
- Surface pumping capability.

The FMEA (D1.1, submitted M4) encompasses the current weaknesses of drilling systems and provides a strong foundation for the project to build upon, allowing its resources to be focused on the current weak points and in parallel, develop new and complementary technologies that can optimise the overall system. Inputs from the project partners, included within this report, assist the project, overall, in how they (project partner) benchmark their processes and how the project, in its entirety, can incorporate these KPIs, so that as the Novel Drilling Systems progresses, the project can continue to evaluate and update goals and milestones, keeping as its core objective, the requirement to drill wells in excess of 5,000m deep, with formation temperatures as high as 250°C, whilst reducing costs.

3. OBJECTIVES MET

The deliverable contributes towards the following work package objectives:

- To review the KPIs relevant to Geo-Drill component performance.

4. KEY PERFORMANCE INDICATORS

4.1 OVERVIEW

As part of its objective to develop a holistic drilling technology, project Geo-Drill will analyse current weaknesses and pinch-points to minimise drilling cost and non-productive time (NPT) and at the same time harvest data from the drilling activity to optimise operational efficiencies (see Figure 1).

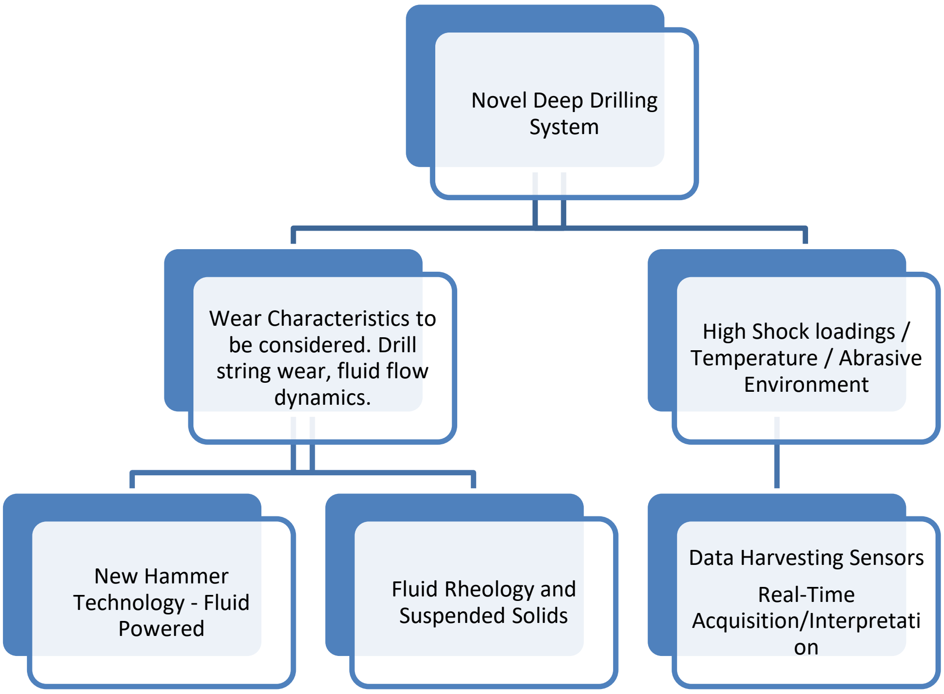


Figure 1. Geo-Drill innovation

The value of any new drilling technology should be benchmarked by its demonstrated geothermal profitability-critical criteria:

- Excavation productivity (m^3/hr);
- Excavation energy efficiency (KWh/m^3);
- Specific borehole cost potential (€/m borehole & cm final diameter)[†].

At this stage of the project, this section is very much an open discussion. A further complication is the complex nature of the sub-surface geological conditions that geothermal wells need to penetrate in order to harness the heat generated — great depth (5,000m +) and high temperatures (250°C). Excluding high enthalpy sources, predominantly "volcanic", which present their own unique drilling challenges, formations with a high geothermal gradient, mainly igneous/metamorphics, that have high strength, high abrasion and possible stress regimes, may present drilling problems, such as wellbore breakouts. Igneous rocks often have faulting/fracture zones that bring additional problems, such as lost circulation and induced deviation. Setting KPIs, therefore, is challenging and need to be done with care, since these will be used as a relative measure of progress. Given that the project is focusing on deep wells, it is essential that all in-hole equipment is reliable and capable of extended life-cycle times. This will reduce the number of trips out of the well to change worn or damaged components, which incur costly NPT and can exacerbate well bore stability. KPIs would, therefore, need to consider the generally acceptable industry standards of life expectancy and then set SMART objectives that can be evaluated in laboratory tests, prior to full scale well tests. It is also essential to consider any potential negative impact that changes of certain components might have on other components or the well-bore environment. The base technology under consideration is a "percussive" hammer system, actuated by a fluid that will carry the cuttings, produced by the drilling action, to the surface. Integrating all of the components into a functioning system is a great challenge, but essential to providing a holistic system.

4.2 Methodology

To evaluate the quality of the performance and to assess the efficiency of components developed, an evaluation methodology based on KPIs has been designed, where a baseline and a range is defined for each KPI. A template (spreadsheet) targeting the different components of the project has been developed which captures the main elements that must be developed for each KPI, including the target, rationale for the KPI, methodology for testing and associated calculation.

The consortium has identified KPIs at the following levels:

Technical KPIs:
These KPIs are defined to establish technological innovations that allow comparison with the current state-of-the art. The definition of these KPIs is essential for the screening process and they will be used to make decisions about materials selections for drill components including sensor development.
Operational KPIs

To measure the success of the overall technology developed. These KPIs will be used during the validation and integration activities in the project.

[†] Report on Geothermal Drilling Date : March 2013 - Authors: P Dumas (EGEC), M Antics (GPC IP), P Ungemach (GPC IP)

4.3 Technical KPIs

WP2 – Development of materials and coatings

Table **1** provides an overview of technical KPIs established for materials and coatings developed as part of the WP2.

Table 1 Overview of technical KPIs for materials and coatings developed in WP2

Component/Material/ Coating	**KPI**	**Test**	**Unit**
GO-WC	Density	Quantitative image analysis of cross-section	%
	Hardness	Vickers hardness	Hv
	Toughness	Charpy[1]	J
GO-PTFE (polytetrafluoroethene)	Water permeation	TBD	g/cm²/s
	Mechanical properties	DMTA (dynamic mechanical thermal analysis)	TBD
	Abrasion resistance	Taber	mg/m
HVOF (high velocity oxygen fuel) coatings	Porosity	Quantitative image analysis of cross-section or permeation test, TBD	% or g/cm²/s
	Microstructure	SEM, EDX, optical microstructure	-
	Hardness	Vickers hardness/nanohardness	Hv/GPa
	Bond strength	ASTM C633 adhesion test	MPa
HIP (hot isostatic press) bonding (teeth)	Bond line microstructure	Image analysis	visual assessment
	Bond/tensile strength	TBD	MPa
HIP bonding (tool joint and stabiliser)	Bond line microstructure	Image analysis	visual assessment
	Bond/tensile strength	TBD	MPa
EL (electroless) nickel coatings	Microstructure	SEM, EDX, optical microstructure	-
	Contact angle	Sessile drop	angle
	Hardness	Vickers hardness/nanohardness	Hv/GPa
HEA (high entropy alloy) & cermet coatings	Porosity	Quantitative image analysis of cross-section or permeation test, TBD	% or g/cm2/s
	Microstructure	SEM, EDX, optical microstructure	-
	Hardness	Vickers hardness/nanohardness	Hv/GPa
	Bond strength	ASTM C633 adhesion test	MPa

[1]Charpy testing provides a quick and inexpensive measure of impact fracture energy, which gives an indication of a material's toughness, but may not be possible for geometries available within the project.

WP: 2 Task 2.3 (Coatings for drill bit tooth, fluidic oscillator and stabiliser)

KPI: Porosity, microstructure, hardness, adhesion strength

Rationale:

Coatings will be developed by HVOF process using different guns that can be potentially applied for drill bit, fluidic oscillator and stabiliser. Coatings will be developed under this task for improved hardness and microstructure as compared with current applied materials, including WC based coatings, Cr_3C_2/NiCr coatings, nickel based self-fluxing alloy coatings, nanocrystalline/amorphous coatings.

1. WC-based coatings
   WC coatings are well-known for their outstanding wear resistance. Many studies showed that WC based coatings exhibited higher hardness, fracture toughness and corresponding anti-wear performance compared with other carbides. WC can be reinforced by binders such as cobalt or nickel.
2. Cr_3C_2/NiCr coatings
   Cr_3C_2/NiCr coatings exhibit good corrosion and wear protection. While WC-based coatings are usually used below 450°C, Cr_3C_2 based coatings can be satisfactorily applied at temperatures up to 900°C, but offer lower hardness and wear resistance than WC based coatings.
3. Nickel based self-fluxing alloy coatings
   The hardness and wear-resistance of such coatings increases as the content of chromium and boron increases. Boron and silicon depress the melting temperature. Such coatings exhibit dense structure and are widely used for components requiring wear and corrosion resistance.
4. Nanocrystalline/amorphous coatings
   Nanocrystalline/amorphous coating types offer a lower cost alternative to WC based coatings, while still providing the required wear and corrosion properties. The larger volume fraction of grain boundaries of nanocrystalline materials (size <100nm) prevents propagation of cracks compared with conventional materials, resulting in increased strength and toughness.

Target: Improvement of hardness and microstructure (porosity) as compared with current applied materials.

Method for measuring: SEM, EDX, optical microscopy, micro-hardness test or/and nanoindentation test, adhesion test.

WP: 2 Task 2.7 (Electroless plated PTFE-based Ni-P coatings)

KPI: Microstructure, contact angle, hardness

Rationale: Ni-P-PTFE has attracted significant interest due to its high melting point, extremely low surface energy and low friction coefficient, which provide excellent abrasion and corrosion resistances.

Target: Higher contact angle as compared with current applied material

Method for measuring: SEM, EDX, optical microstructure, sessile drop, Vickers hardness/nanohardness.

WP: 2 Task 2.8 (HEA and cermet coatings)

KPI: Porosity, microstructure, hardness, adhesion strength

Rationale: High Entropy Alloy (HEA) and cermet coatings will be developed through HVOF that can be applied for drill components to improve their wear and corrosion resistance.

1. HEA coatings developed rapidly over the last decade, owing to their outstanding properties such as high yield strength and ductility, microstructural stability and retained mechanical strength at elevated temperatures.
2. Ceramic –metallic materials, "cermets", are often considered in service involving high erosion and corrosion conditions where ceramic particles provide a high erosion resistance and metallic binder phase makes the coating more ductile than a pure ceramic coating.

Target: Improvement of hardness and microstructure as compared with current applied materials.

Method for measuring: SEM, EDX, optical microscopy, micro-hardness test or/and nanoindentation test, adhesion test

WP3 – Material Characterization and Testing

Table 1 provides an overview of technical KPIs established for materials and coating that will be characterized and tested in WP3.

Table 2 An overview of technical KPIs for materials and coatings developed in WP3

Component/Material/Coating	**KPI**	**Test**	**Unit**
GO-WC & GO-PTFE bulk materials	Microstructure	SEM, EDX, optical microstructure	-
	Hardness	Vickers hardness/nanohardness	Hv/GPa
	Wear rate	Tribological test (Pin on Disk (PoD); sliding test in reciprocating motion; ring on ring test)	mm^3/Nm
	Coefficient of friction	Tribological test (Pin on Disk (PoD); sliding test in reciprocating motion; ring-on-ring test)	(unitless)
	Corrosion rate	Corrosion testing in simulated drilling environment	mm/year
	Erosion-corrosion rate	Slurry pot test measuring weight loss/corrosion rate	mm/year or (g/cm^2hr)
	Wear-corrosion rate	Tribo-corrosion tests (PoD)	mm/year
HVOF coatings; HEA & Cermets coatings; El nickel coatings	Microstructure	SEM, EDX, optical microstructure	-
	Hardness	Vickers hardness/nanohardness	Hv/GPa
	Bond strength	ASTM C633 adhesion test	MPa
	Wear rate	Tribological test (Pin on Disk (PoD); sliding test in reciprocating motion; ring-on-ring test)	mm^3/Nm
	Coefficient of friction	Tribological test (Pin on Disk (PoD); sliding test in reciprocating motion; ring-on-ring test)	(unitless)
	Corrosion damage	Corrosion testing in simulated drilling environment	no. of cracks and delamination
	Erosion-corrosion rate	Slurry pot test measuring weight loss/corrosion rate	mm/year or (g/cm^2hr)
	Wear-corrosion rate	Tribo-corrosion tests (PoD)	mm/year

WP: 3 Task 3.1 (Mechanical Testing and Microstructural Characterization of coupons)

KPI: microstructure, hardness, adhesion strength, wear rate, coefficient of friction

Rationale:

The bulk materials and coatings developed in WP2 will be analyzed by mechanical testing and microstructural characterization to evaluate the integrity of the materials before corrosion and erosion testing them. The hardness will be measured and compared to SOA materials currently used to evaluate if improved hardness has been achieved. The tribological behavior of the materials developed will be evaluated by tribological testing (PoD/linear/RoR) to measure wear rate, coefficient of friction (CoF) at temperatures and in medium relevant to geothermal drilling environment. Decreased CoF and wear rate compared to SOA will improve the abrasion and wear resistance. The microstructure of the developed materials needs to be examined before comparison to corrosion and erosion tested materials to evaluate the bonding and uniformity of the coatings and material distribution (uniformity) and porosity of the bulk materials.

Target: Improvement of hardness and microstructure, lowering of CoF and wear rate compared to current applied materials.

Method for measuring: SEM, EDX, optical microscopy, micro-hardness test or/and nanoindentation test, adhesion test, tribological tests (PoD, linear, ring-on-ring).

WP: 3 Task 3.2 (Corrosion testing in simulated geothermal drilling environment); Task 3.5 (Evaluation and ranking of a developed materials and coatings); Task 3.4 (HTHP testing and evaluation of sensor and cable material)

KPI: corrosion rate, corrosion damages (cracks, delamination, permeation)

Rationale: To assess if the developed bulk materials and coatings produced in WP2 have improved properties (corrosion resistance) compared to current SOA materials used in geothermal well drilling the materials need to be tested at elevated temperature and pressure as materials experience in geothermal well drilling environment (well-bore environment). This will be done by testing the developed materials in high temperature (250°C) and pressure, and simulated geothermal drilling environment in laboratory and assess the damages of SOA material compared to new Geo-Drill developed materials by measuring corrosion rate and assessing the materials damage.

Target: corrosion resistance compared with current applied material tested also in the simulated drilling environment.

Source/Formula

Method for measuring: SEM, EDX, XRD, optical microscopy, weight loss measurements.

WP: 3 Task 3.3 (Erosion-corrosion testing in simulated geothermal drilling environment)

KPI: erosion-corrosion rate (g/cm^{2}hr), corrosion rate

Rationale:

Erosion-corrosion tests will be performed with slurry pot equipment at RT to access whether the developed bulk materials and coatings in WP2 have improved erosion and erosion-corrosion resistance to SOA materials currently used in geothermal well drilling.

Target: Improvement of erosion and erosion-corrosion resistance compared with current applied materials.

Method for measuring: Electrochemical workstations, slurry-pot test

4.4 Operational KPIs

Overall Rate of Penetration (ROP) expectations for drilling in hard sedimentary, metamorphic and igneous formations currently range from 25m – 5m per hour (formation dependent). Any increase in ROP represents a cost saving, directly attributable to the number of days saved.

In most wells, the key hole diameters are 17.5” (445mm) and 12.25” (311mm) for the installation of 13 3/8” and 9 5/8” casing, respectively. Therefore, it makes sense to concentrate on drilling these sections more quickly and with the minimum number of “trips” (the process of pulling the drill string from the well and running back in with a new bit).

Table 2 Possible Cost Savings

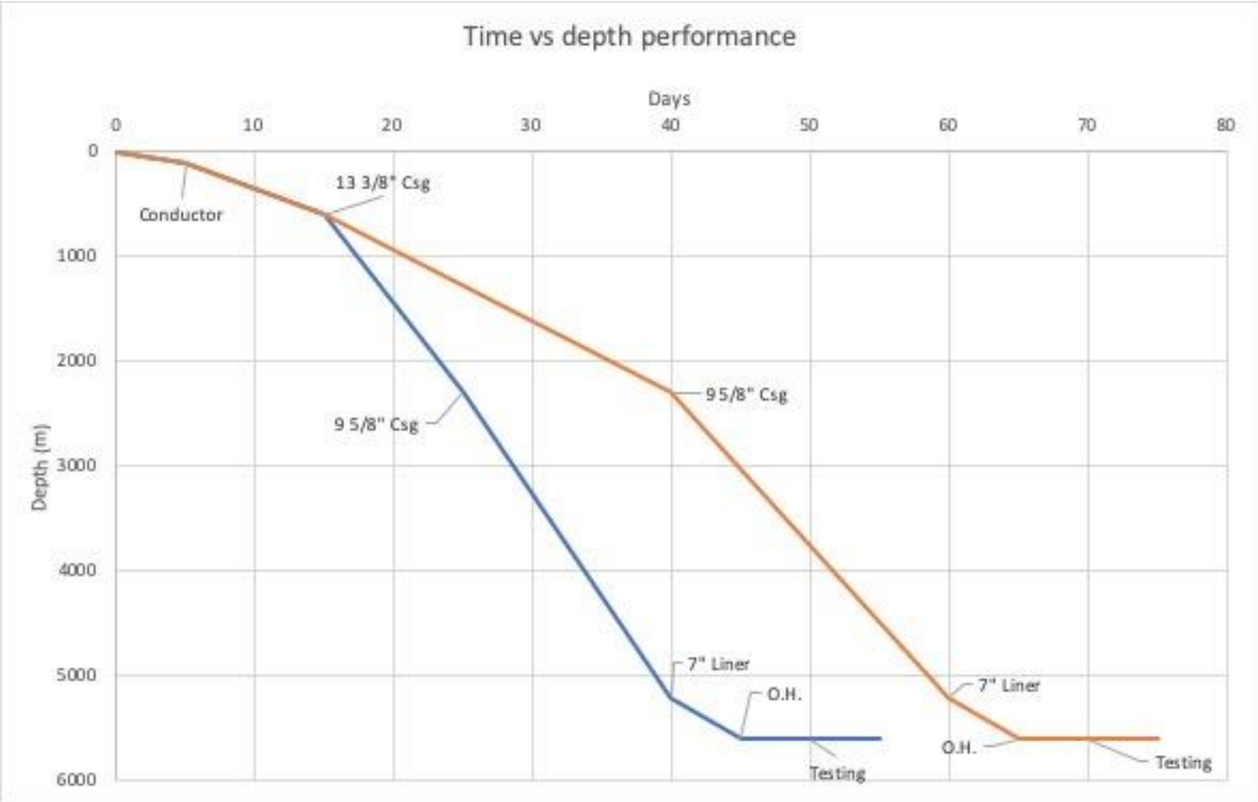
Drilling System	Hole Section	Depth Drilled (From shoe to shoe)	Time to Drill (Hours)	Bits Used (Size/No./Cost € each)	Guide Total €
Rotary Drilling System (IADC Code: 635 – Major Manufacturer)	17.5”	800m (200m – 1,000m)	160	17.5”/ 3 / 20,000	393,280
	12.25”	1,500m	300	12.25” / 3 / 18,000	678,900
Fluidic Percussion Drilling System	17.5”	800m	80	17.5” / 1 / 18,000	184,640
	12.25”	1,500m	150	12.25” / 1 / 15,000	327,450

Table 3 Operating Parameters

Drilling Method	Depth Range (Metres)	UCS (MPa) (optimal)	Average ROP m/hour (150 MPa)	Notes
Conventional Rotary	6,000 +	20 – 80	5 to 1	Tricone roller bits require high Weight On Bit (WOB). Can operate in high-pressure, high-temperature (HPHT) conditions.
PDC (polycrystalline diamond coated) Rotary	6,000 +	30 – 80	Not Recommended	Particularly effective in sedimentary and lower strength metamorphics. Work well with PDMs (positive displacement motors). In harder/stronger formations, modified PDC bits can be used – diamond Impregnated – but at very high cost.
Air Percussion DTH hammer	4,000*	40 – 320	12	*Dependent on formation fluids (annular back-pressure). Requires high-pressure air pack. In some formations ROPs as high as 65m/hr have been achieved. Ideal in zones with loss of circulation.
Water Powered DTH hammer	>3,000*	40 – 350	15 up to 1m / min	* No physical limit as in Air Percussion, requires sufficient high quality water supply to avoid high internal wear of hammer components.
Novel Fluidic Mud Hammer	5,000+	40 – 350	15 up to 1m / min	The ability to flow a Mud like liquid through the hammer, will take the current water powered hammer to new levels of capabilities, safety, borehole stability, service life as well as dealing with elevated formation temperatures.

Currently, most DTH hammer systems have a maximum operating temperature of 150^{0}C, but with the utilisation of special sealing systems, Geolorn has been operating air hammers at temperatures close to 200^{0}C, although often the circulating temperature usually is substantially lower (especially with air flush) than the static/recovered temperature.

The goal for the Novel DTH Fluidic Mud Hammer is to operate in circulating temperatures as high as 250^{0}C.



(Data courtesy of Geolorn Ltd – 2017)

Conventional Rotary Drilling — Percussive Hammer Drilling

Figure 2 Time vs depth performance of different drilling systems

Figure 2 demonstrates the potential savings in time, utilising a percussive drilling system, such as that under development by the Geo-Drill Consortium. The fluidic hammer, unlike pneumatic percussive hammer drilling, is less affected by formation fluid flows and pore pressure. A 3,000m deep geothermal well, drilled in a sedimentary basin, typically takes around 45 days to drill and complete; an equivalent shale gas well, drilled in the Eastern USA has a completion time around 10 days. The latter is commonly drilled with a combination of air percussion and mud rotary (fixed cutter PDC).

Potential Savings

Example:

Base rig operating cost of 50,000€ / day. Days saved = 20. Cost savings = 20 x 50,000 = 1,000,000€uros

As rock strength increases, cost savings increase significantly.

Table 4 Hammer Componentry & Drill String Life Expectancies

Component	**Current Life Expectancy** **1. Sedimentary** **2. Metamorphic** **3. Igneous[1]**	**Target Life Expectancy** **1. Sedimentary** **2. Metamorphic** **3. Igneous**	**Current Material(s)**	**Notes**
Button Inserts	1. 2,000m 2. 1,000m 3. 500m ***Assumes Inserts are sharpened.***	1. 4,000m 2. 2,000m 3. 1,000m	Sintered Tungsten Carbide/ PDC Coating Through-hardened substrate.	Lab evaluation testing for assessing current inserts and possible improvements for abrasion resistance and fracture failures. Coatings. If any.
Hammer Bit Body Including Shank and Striking Face	1. 2,500m 2. 1,500m 3. 750m	1. 5,000m 2. 3,000m 3. 1,500m	Hardened & heat treated alloy steels. Surface treated.	Lab evaluation testing for improved abrasion resistance and fracture failures. Coatings.
Hammer Assembly (Fluid Operated)	3,000m	5,000m+	Various alloy steels, with various surface treatments. Generally, solids greater than 7µm in size, are considered to be detrimental to hammer life.	Due to the complexities of the internal workings of the hammer, the nature of the fluid(s) to be used and their various functions in the overall process, an integrated testing programme will be required to fully understand where improvements can be made.
Drill String Components (Collars, Pipes, Stabilisers)		10,000m		1,000 Hours Rotating time[2]

[1] ***Igneous: UCS >250 MPa, High Silica./ Metamorphic: UCS 120 – 150 MPa, Possible Quartzite/ Sedimentary: UCS 50 – 120 MPa, Low Abrasion (For guidance only)***

[2] ***For testing and evaluation purposes, we will have a target Rate of Penetration (ROP) of 10m/hour in igneous formations, so the target life cycles need to be divided by 10, to give rotating hours on bottom.***

5. CONCLUSIONS

At this point of the project, more questions have been raised and how best to build upon existing technologies, incorporate the new technologies and how the consortium can leverage its internal knowledge base.

The project has adopted accepted KPI protocols for many of the processes and will modify these as necessary step-by-step. It will also be required to look at some processes in a whole new way, as the Novel Technologies are developed. This is imperative to accommodate the system as a whole, rather than individual parts, hence the need for reviews and updates as the technologies are developed and incorporated.

KPIs, therefore, need to be carefully thought through, so that unknowns (as listed above) can also be encompassed within the project's objectives.

Key points at this stage of the project:

- Improve the life-cycle of drill bits. Changes to substrate materials, surface coatings.
- Build a robust fluid activated hammer, capable of operating at great depths (high pressure/high temperature environments).
- Develop surface coatings that provide longer wear resistance for the internal parts of the hammer, permitting the use of fluids that require less surface treatment/cleaning (larger suspended particle size).
- Develop cost-effective coatings for the drill string components, that reduce frictional/pressure losses internally and externally, and reduce erosional wear.