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DELIVERABLE D4.2

EHS comparison of DeepU with conventional drilling technologies

WP4

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Publishable summary

D4.2 is a comparative document which reviews the EHS procedures related to Environmental Health and Safety in deep drilling operations. The document compares applicable procedures from the oil, gas and geothermal sectors for onshore drilling operations and the requirements under legislation for the implementation of an EHS plan at a well site. The EHS procedures considered as part of the conventional drilling method are assessed in the deliverable against the new DeepU drilling methodology and considerations are given through a detailed risk assessment of the required measures to be implemented when using the DeepU method. The document also provides a Failure Mode & Effects Analysis (FMEA) and outline measures for mitigating such failures to allow further development of the DeepU technology. The outcomes of the deliverable are proposed in the context of the development of the DeepU drilling technology in the future and will provide the basis for recommendations to be implemented allowing the DeepU drilling method to achieve regulatory acceptance and commercialisation.

Abbreviations

BOP	Blow Out Preventer
CAPEX	Capital Expenditure
D	Deliverable
DeepU	Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation
DHN	District Heating Network
EHS	Environmental Health and Safety
EIA	Environmental Impact Assessment
FMEA	Failure Mode and Effects Analysis
HE	Heat Exchanger
OHS	Occupational Health and Safety
T	Task

1 INTRODUCTION

This report sets out to define current industry standards for the drilling of deep geothermal wells and the characteristics required to be incorporated within the Novel System under development by the DeepU Consortium.

One of the key issues of current deep geothermal projects, is the need to utilise technology and methodologies from hydrocarbon exploration and production drilling, which have historically high costs attached to them, although with waning demand (driven by climate change awareness) this is decreasing somewhat. Therefore, the geothermal industry requires a “bespoke and fit-for-purpose” drilling system, capable of withstanding high formation temperatures, high strength rocks, high pressures (depth related) and aggressive formation fluids (typically brines). At the same time, this new drilling technology must be reliable, simple to operate and be cost-effective in the drilling process.

Whereas hydrocarbon reservoirs are within sedimentary and **metasedimentary** formations (**with some target zones below igneous and volcanic formations)**, the potential for sustained geothermal production **from** within high strength igneous rocks, with good thermal properties and heat profiles, **is an increasing target area.**

Such formations pose particular problems not generally associated with deep **hydrocarbon** drilling and therefore require a novel drilling system, that reduces specific energy inputs and allow for increased overall penetration rates through the reduction of failures associated with mechanical contact drilling technologies.

With the increasing demand for “base-load” (heat/power production that has a constant and predictable delivery profile), that is low carbon and close to centres of populations, deep drilling into high strength/high heat formations is set to rise dramatically. Unlike oil and gas, heat energy is not easily transported over great distances and as the predominant energy usage is for heating, it makes eminent sense to avoid further energy losses due to converting heat into electrical energy, and converting it back to heat. This is particularly relevant where heated water can be piped to domestic, commercial and industrial end-users and recirculated to be reheated by the rocks at depth. Geothermal drilling systems need to have the following characteristics:

- The ability to drill in varying lithologies, including micro-crystalline rocks, with high strengths, at rates of penetration that are substantially higher than conventional rotary drilling;
- The ability to withstand abrasion;
- The ability to withstand prolonged stress loading;
- The ability to move cuttings, produced by the drilling, long distances to the surface;
- The ability to cope with changeable down-hole conditions, without the need to trip out of the well;
- The ability to provide real-time information from the bottom of the well to the “driller”, so that the whole operation can be continuously optimised;
- The ability to be integrated with existing surface equipment, to minimise CAPEX to the industry.
- Be simple to operate, be cost effective and readily available;

Whilst all of the above are reasonably achievable, individually, the challenge of combining them all together is a substantial challenge, but through the adoption of a new approach to solving the issues, holistically, a whole new era of lower cost geothermal wells are within reach.

The DeepU technology aims to address all of the above points, but as with all innovative processes there will be new and possibly unique operational risks that require to be identified, quantified and where possible removed or mitigated for.

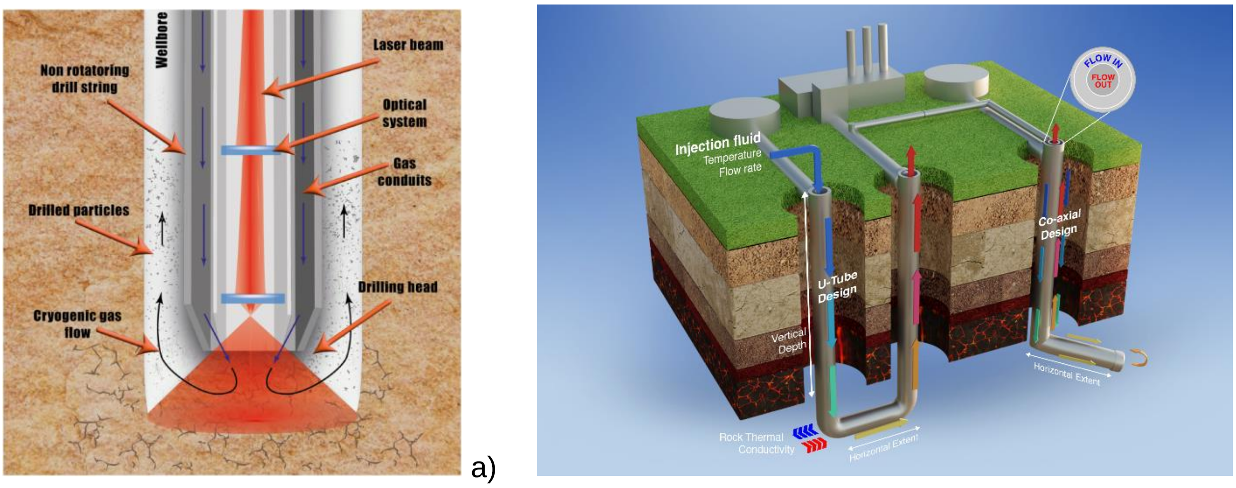
2 OBJECTIVES

The objectives of Task 4.2 covered in this deliverable are to undertake an Environmental Health and Safety risk assessment of the DeepU technology focussed on comparing this with the requirements set out for drilling operations using conventional mechanical drilling methods.

The purpose of this document is to report on the outcomes of Task 4.2 at the present state of development of the DeepU drilling system in order to make recommendations on the future development and deployment strategy of the non-mechanical drilling system for compliance with existing regulatory requirements for the drilling sector. Such recommendations are to be covered in task 4.3 of the project.

3 THE DEEPU DRILLING PROCESS

The DeepU drilling methodology is focussed on utilising non-mechanical drilling methods to improve drilling process efficiency, increase penetration rates leading to a reduction in overall time on site and cost compared to current mechanical methods available on the market. The DeepU process focusses on using a high-power industrial laser system to allow spallation and melting of rock formations to create a borehole. The drilling system is supported by a supercritical gas flushing system that allows the removal of spalled, melted and solidified particles from the spallation process to be transported to the surface. The objective of the DeepU process is to allow for drilling of deep boreholes to depths of 4,000m or greater, to complete a closed U-tube heat exchanger allowing harnessing of deep geothermal heat for power generation and direct use (figure 1).



a) b)

Figure 1 – Conceptual design objectives of the DeepU technology: a) general process schematic of the DeepU drilling method; b) conceptual design of a deep closed loop geothermal system [2]

The non-mechanical DeepU process therefore significantly differs from conventional mechanical drilling methods that use rotating drill strings and a fluid (mud) or air (compressed) based flushing system for clearing cuttings and controlling wellbore conditions. The difference between the methods, requires careful review of the drilling process methodologies and an assessment of the Environmental Health and Safety aspects related to applying these (figure 2).

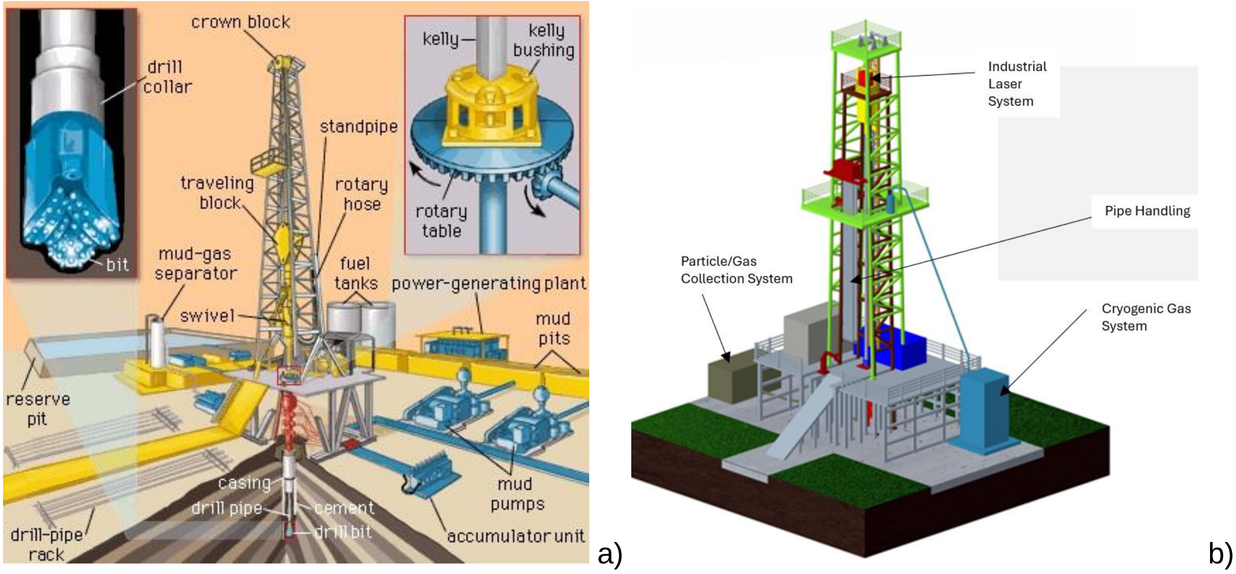


Figure 2 – Conceptual design objectives of a) deep drilling, mud rotary system [3]; b) the DeepU technology

Table 1 - Key differences between Conventional and DeepU drilling

Conventional		DeepU	
Lithologies are broken into small chip/particles, through the application of weight being applied, creating shear or crushing action.	Requires relatively high energy inputs to achieve the crushing or shearing of lithologies.	Lithologies are subjected to high temperatures, resulting in spallation or melting/evaporation.	Requires high energy laser to heat the wellbore. Industrial lasers have unique operating conditions.
Chips/particles require to be flushed from the wellbore.	Requires pressurising either fluids (muds) or air, which requires high energy inputs.	The lithologies go through phase changes, as the heat increases.	To move particles out of the wellbore requires a gas flush. This will be achieved through the use of cryogenic gas (Nitrogen).
Introducing fluids into the wellbore to flush cuttings.	Risk of fluids entering formations. Risk of uncontrolled spillages on the surface, leading to environmental issues. Increased usage of additives.	Ultra-low temperature cryogenic gas/Super-Critical Fluids	Completely novel approach to deep drilling and will have unique EHS parameters and operational conditions. Need to understand phase changes within the wellbore and any affects.
Use of high-pressure air.	Possible issues with wellbore stability. Lower environmental issues. Limited hydrostatic pressure, leading to issues when drilling over-pressured formations.	Returning cryogenic gas returning to surface loaded with cuttings.	Cuttings will require to be separated from the gas flow at surface with the gas being released to atmosphere. Understanding possible environmental issues, although nitrogen gas is commonly used in both drilling and industrial applications.
Mechanical wear of drill bits and drill string.	Increased number of trips in and out of the wellbore to change components. Increase in risks to personnel and/or environment. Increased use of raw materials.		

4 METHODOLOGY

The assessment of the environmental health and safety aspects of the Deep U method has been based on applying two methodologies aimed at assessing the risks associated with the DeepU process and at identifying suitable mitigation measure that may be applied as part of the later phases of the project process to mitigate such risks. These two methods include:

- A Failure Mode & Effects Analysis (FMEA); and
- An Environmental Health and Safety Risk Assessment

The principle behind the implementation of both of these methods is aimed, in the first instance, at assessing the technological solutions developed as part of the DeepU drilling system to identify any potential modes of failure (through equipment or process) causing potential risks. In the second part, the EHS risk assessment considers the aspects of the novel drilling technology in the context of the approval process for drilling operations, considering drilling operations risk management, how standard drilling legislation and practises would fit with DeepU system.

4.1 DEEP DRILLING EHS CONSIDERATIONS

An extensive literature review carried out in D4.1 of the DeepU project, was used to assess the current legislative and regulatory environment associated with onshore deep drilling operations in a number of jurisdictions.

Since the legislative and regulatory review completed in the early phases of the project, the DeepU technology has evolved following successful experimental results in the operation of the laser, the improved design of the drill string and the development of a gas flushing process that addresses the risks identified throughout the development. The EHS assessment completed as part of this deliverable is focussed (but not limited to) the current risks mitigation requirements identified as critical for further technology development against existing legislation, regulations and standards.

At the time of writing the deliverable, the following critical considerations were highlighted based on the development of DeepU to date:

- The requirement for the development of specific operational procedures for the DeepU drilling system as these vary considerably with the current state of the art mechanical drilling methods;
- The use of an industrial scale laser and the need for integrating a controlled operational environment as part of the drilling process;
- The use of a cryogenic gas as part of the drilling process to flush cuttings and control the wellbore;
- The requirement for deployment of formation evaluation methodologies to allow measurements and incident mitigation measures to be implemented during the drilling process
- The requirement to drill to achieve a U-tube configuration completion for the operation of the final system;
- Hole integrity over the life time of the project below the cased section where no casing or external material applied to the wellbore wall
- Abandonment & Decommissioning requirements
- The need for widespread training and certification of specialist personnel to ensure widespread deployment in a commercial manner.

The subsequent sections of this deliverable demonstrate the FMEA and EHS Risk Assessment process applied throughout the project to put in place suitable mitigation measures that address these risks as well as highlighting the ongoing work.

5 FAILURE MODE & EFFECTS ANALYSIS (FMEA)

FMEA is a tool used to identify and prevent product and process failure before it occurs [1] (figure 3). Such failures can either occur through a process or component failures, or through the reduction of performance of a key process component. Once identified, the failure modes can then be rated based on the severity (S) of each effect, the frequency of occurrence (O) and its detectability (D) (figure 4).

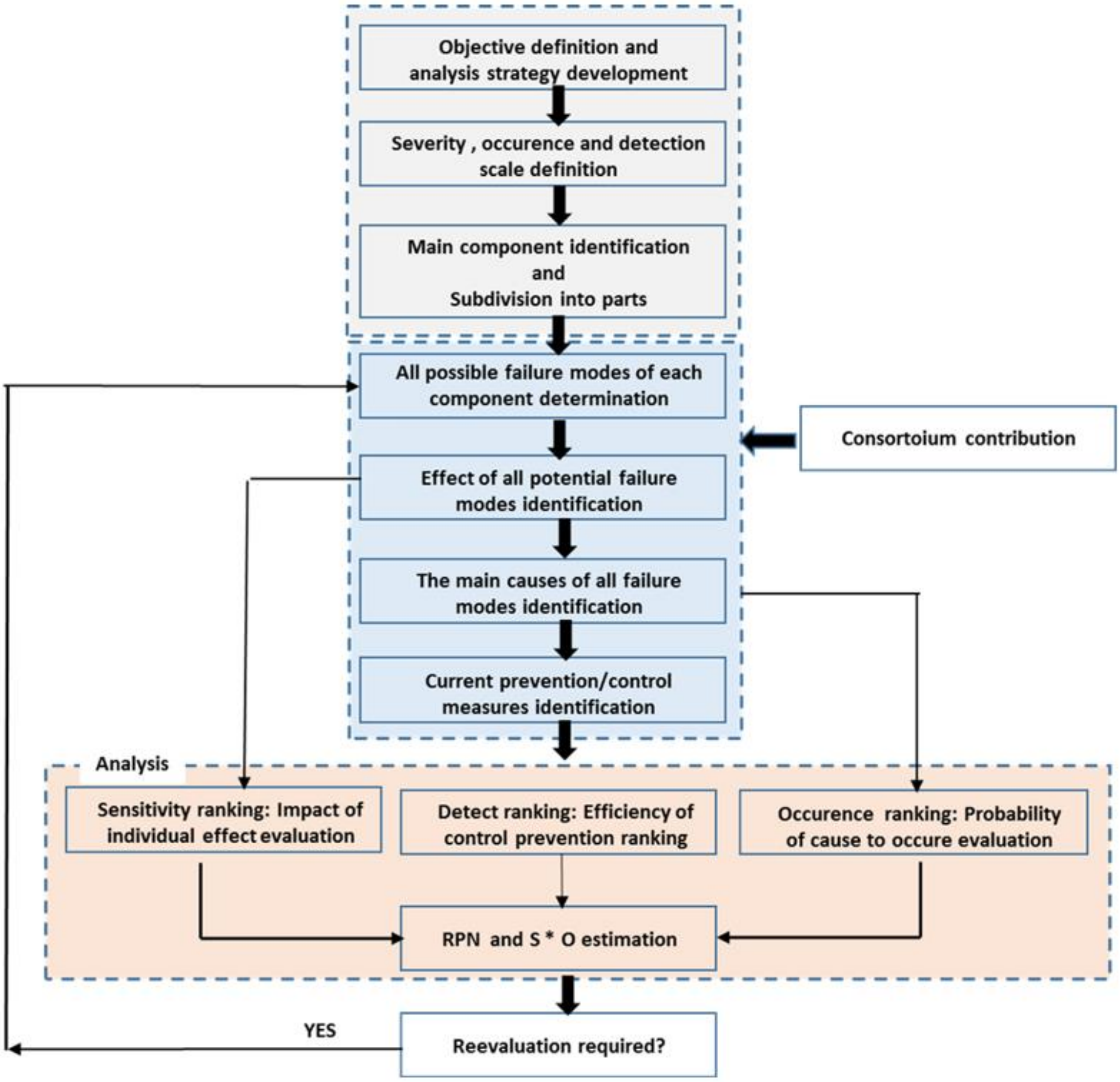
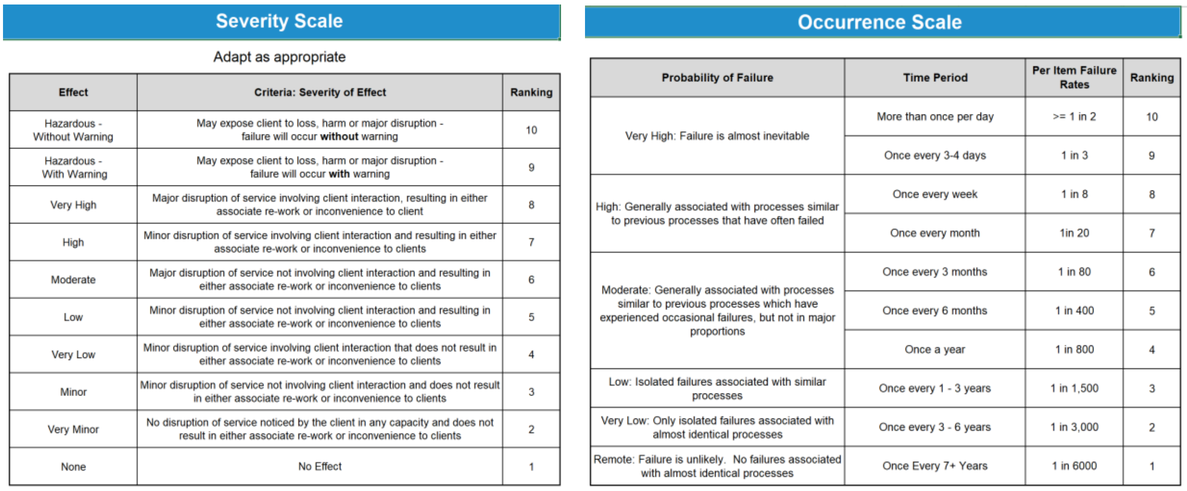


Fig 3. The FMEA process



Severity Scale

Adapt as appropriate

Effect	Criteria: Severity of Effect	Ranking
Hazardous - Without Warning	May expose client to loss, harm or major disruption - failure will occur **without** warning	10
Hazardous - With Warning	May expose client to loss, harm or major disruption - failure will occur **with** warning	9
Very High	Major disruption of service involving client interaction, resulting in either associate re-work or inconvenience to client	8
High	Minor disruption of service involving client interaction and resulting in either associate re-work or inconvenience to clients	7
Moderate	Major disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	6
Low	Minor disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	5
Very Low	Minor disruption of service involving client interaction that does not result in either associate re-work or inconvenience to clients	4
Minor	Minor disruption of service not involving client interaction and does not result in either associate re-work or inconvenience to clients	3
Very Minor	No disruption of service noticed by the client in any capacity and does not result in either associate re-work or inconvenience to clients	2
None	No Effect	1

Occurrence Scale

Probability of Failure	Time Period	Per Item Failure Rates	Ranking
Very High: Failure is almost inevitable	More than once per day	>= 1 in 2	10
	Once every 3-4 days	1 in 3	9
High: Generally associated with processes similar to previous processes that have often failed	Once every week	1 in 8	8
	Once every month	1in 20	7
Moderate: Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions	Once every 3 months	1 in 80	6
	Once every 6 months	1 in 400	5
	Once a year	1 in 800	4
Low: Isolated failures associated with similar processes	Once every 1 - 3 years	1 in 1,500	3
Very Low: Only isolated failures associated with almost identical processes	Once every 3 - 6 years	1 in 3,000	2
Remote: Failure is unlikely. No failures associated with almost identical processes	Once Every 7+ Years	1 in 6000	1

Fig 4. Severity and Occurrence Scales used in the FMEA process

As outlined in earlier sections the DeepU drilling process has a number of differences to conventional rotary and percussion drilling methodologies, yet many of the EHS and Operational Health and Safety (OHS) are the same. These are summarise and listed below:

- Drilling site safety as laid out by regional, national and global edicts.
- Environmental risks associated with the uncontrolled release of formation fluids.
- Worker safety associated with drill site operations.
- Noise emissions/pollution.
- Vehicle movements on and off-site.
- High pressure fluids/gases (storage, pipework, connections).
- Temporary lighting and light pollution.
- Visual impacts of drill towers.
- Public safety and environmental hazards.

Based on the processes considered as part of conventional drilling operations and those planned for the non-mechanical DeepU method, an assessment of the possible failure modes for the DeepU equipment and processes has been completed.

A summary of the FMEA is included in Appendix A. The FMEA has outlined a series of actions for implementation throughout the project development process aimed at mitigating the failure modes and improving the DeepU processes. The FMEA processes considered include the following:

- Cryogenic Gas
- Drill String Components
- Laser
- Completions:
    - Overburden
    - Sedimentary formations
    - Igneous
    - Metasediments

The outcomes of the FMEA were used as part of the assessment to complete a technology roadmap (section 7) to determine requirements for development of the DeepU technology as the project progresses. An example of the FMEA is shown in Appendix A of this public deliverable, however, the full content is reserved for deliverable D4.3.

6 ENVIRONMENTAL HEALTH AND SAFETY RISK ASSESSMENT

The EHS Risk assessment workflow applied to assess the DeepU drilling system is focussed on two key aspects that consider Occupational Health and Safety (OHS) and the principles of environmental protection as outlined in EU Directive 2014/52/EU on the assessment of the effects and impacts any project, including those involving deep drilling operations.

The scope and methodology of the DeepU EHS Risk Assessment is focussed on identifying potential leading risk indicators for deep drilling operations and assessing how these would compare with conventional drilling methods. The drilling process, weather using mechanical or non-mechanical drilling methods, is a multi-stakeholder process and organisational factors play a crucial role in risk management and mitigation measures which can only be taken into consideration with the identification of applicable EHS risks and the implementation of a comprehensive Process Safety Management system which involves all stakeholders associated with a drilling project.

The principles of process management safety in the drilling industry are focussed on elimination of inherent process risks at the design stage as the most effective and primary mitigation step. Where any risks cannot be removed, additional measures to prevent, detect control and mitigate such risks are put in place accordingly (figure 5).

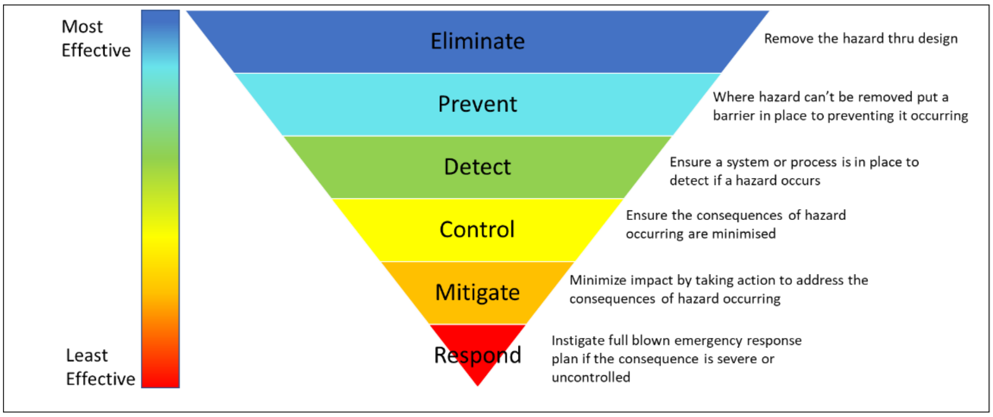


Figure 5. Process Safety Management step hierarchy

When comparing the conventional mechanical drilling methods to the DeepU process, a multistakeholder approach can be considered as part of the safety management workflow based on the individual roles and responsibilities on a drill site. Figure 6 compares the key drilling process stakeholders for mechanical (figure 6a) and DeepU (figure 6b) drilling technologies.

Critically important to the implementation of an EHS risk assessment for DeepU is to consider at the outset the difference in technology readiness between mechanical drilling methods and the DeepU process. Whilst, conventional drilling processes and operational safety management systems are highly regulated, extensive application over several decades has provided ever increasing opportunities to gather lessons learnt and improve operational and environmental EHS management processes across several stakeholders and processes which are critical to the success of drilling operations.

DeepU, on the other hand, is in current state of initial development (TRL 3) with the implementation of the non-mechanical drilling method being trialled at laboratory scale, through the combination of independent processes such as the use of industrial lasers combined with the use of cryogenic fluids being tested to optimise the DeepU process. This task has therefore been focussed on addressing the existing EHS safety process management systems for the main DeepU drilling components applied in a controlled environment such as that trialled at laboratory scale in this project, with an attempt to look ahead to the integration of such technologies and how these may be considered at a drill site.

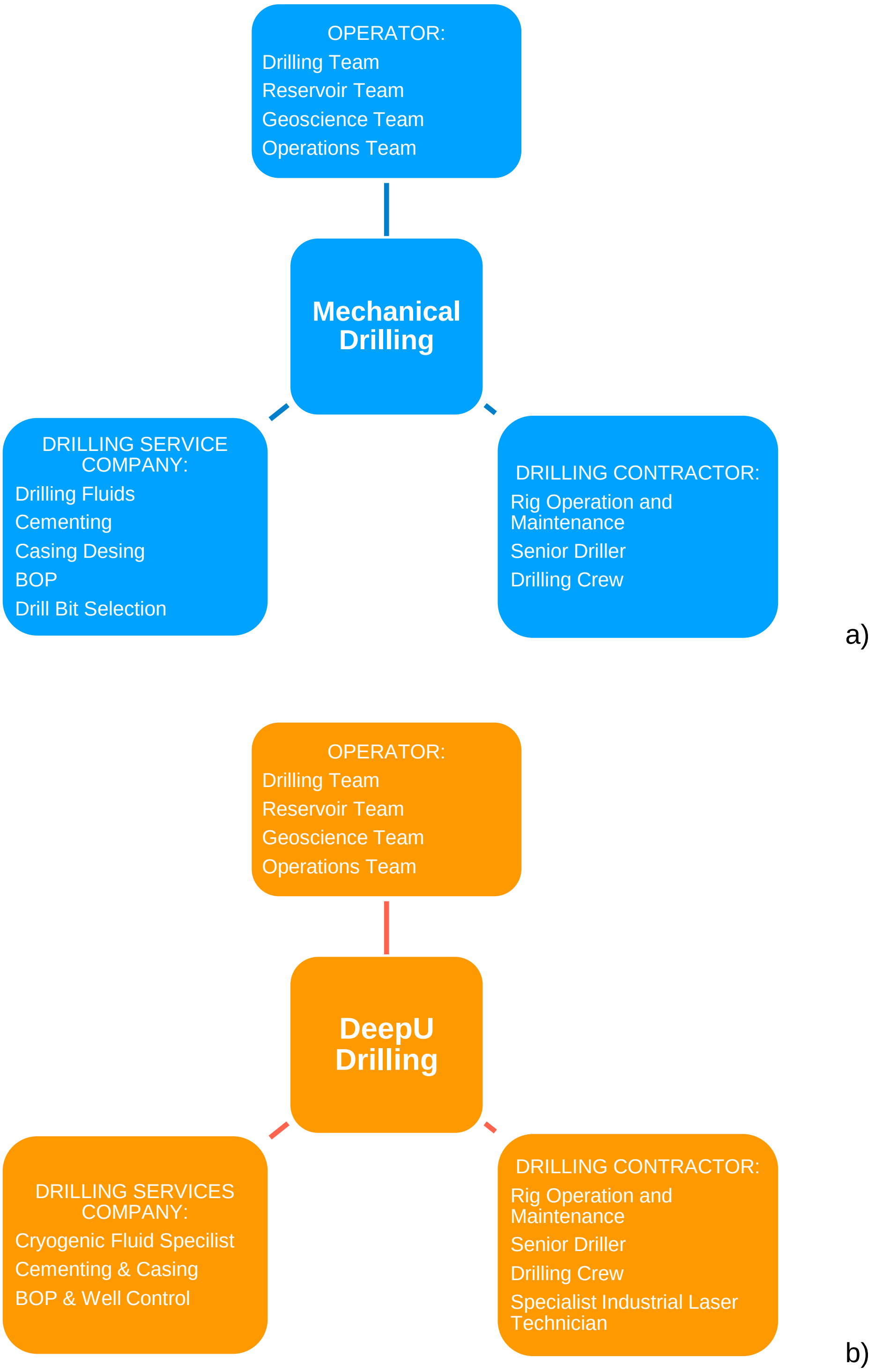


Figure 6. Multi-stakeholder operational requirements for a) mechanical and b) DeepU drilling processes

6.1 EHS Indicators – Comparing Conventional with DeepU

Several organizations including the UK Health and Safety Executive (UK HSE), the American Petroleum Institute (API), the International Oil and Gas Producers (IOGP) and the Institution of Chemical Engineers (IChemE) published guidelines on developing process safety indicators for general hazards and different upstream, downstream processes associated with drilling.

UK HSE published guidelines [4] to assess different categories of indicators associated with drilling operations. Two key classifications are used in the definitions, with **leading indicators** defined as **active monitoring systems for operational and organizational controls placed to prevent** any unwanted situations. Whilst, **lagging indicators are defined as reactive measures** which are the outcome of the risk control system as designed (figure 7).

The guideline introduces a dual assurance, where leading and lagging indicators can be assessed and perform in combination in a structured and systematic way of defining each critical risk control factor.

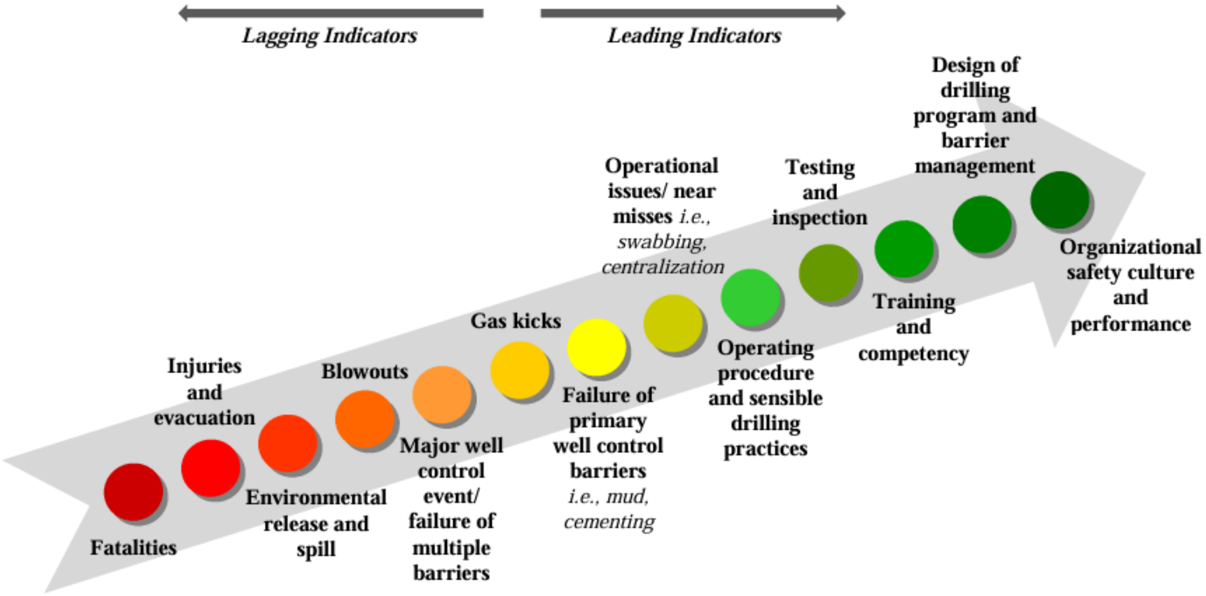


Figure 7. Leading and Lagging EHS Indicators in the drilling process [4]

An example of well control focusing on blowout incidents can be considered with the concept of leading and lagging indicators. Flow of uncontrolled well fluids into a wellbore and to the environment is called a blowout. As blowouts are low frequency-high consequence events, lagging indicators cannot offer a good control measure because having a low past incident rate or low rate of gas kick events does not eliminate or help predict the chance of a future uncontrolled gas kick resulting in a blowout.

In the assessment of the DeepU drilling process, this task has therefore considered the importance of the potential lagging indicators associated with the non-mechanical laser-based drilling method and assessed these to identify leading that need to be considered as part of the technology development process and its integration to deep drilling sites.

The key indicators for the DeepU drilling system are summarised in table 2 below.

Table 2 - DeepU EHS Indicators

EHS Indicator	Conventional Drilling	DeepU
GENERAL OPERATIONAL H&S Practices	Extensive Guidance & Experience Available	To be established – A detailed EHS Process for the operation of the DeepU drilling processes needs to be established
Drilling Programme Design and Well Plan	Extensive Guidance & Experience Available	A drilling programme to consider different geological scenarios should be developed and well plan to include surface protective casing established prior to using the Laser drilling method
Training & Certification (equipment & personnel)	Extensive Guidance & Experience Available	Extensive Training & Certification plan required for skilled personnel which will require integration with other industrial sector applications
Well Control & Barriers	Extensive Guidance & Experience on Drilling fluid selection/management, the use of BOPs, and casing barriers	No primary well control. N_2 lowers fire risk however additional requirements for integration of BOP
Environmental Management	Extensive Guidance & Experience Available	To be developed and aligned with industrial laser, cryogenic and drilling process requirements
Incident Management Reporting	Extensive Guidance & Experience Available	To be developed and aligned with industrial laser, cryogenic and drilling process requirements
Emergency Response Plan	Extensive Guidance & Experience Available	X –'Wild well' conditions require additional planning and Safety Management process to be developed

6.2 EHS for Drill Sites using the DeepU Technology

The Environmental Health and Safety risk assessment for drilling operations forms an integral part of the development and planning of any deep drilling project. Based on the outline of the regulatory requirements outlined in the earlier part of the DeepU project [5], an EHS risk assessment approach was developed as part of this task to address the critical DeepU processes. The EHS risk Assessment has considered general H&S operational processes, environmental considerations the long term development and abandonment aspects based on the outcomes of the initial technology developments completed in WP1 and WP2 of the project. These are focussed on the DeepU design and testing of a new drill string and laser head for non-mechanical laser drilling method and completion strategy of deep closed loop heat exchangers.

In addition to the above, the processes associated with the use of cryogenic gas for flushing and management of the drilling operations that are proposed as part of the new method in WP8 have also been carefully considered and compared to those requirements associated with conventional drilling where drilling muds and well control processes are extensively documented.

The completion and long term operation of a deep closed loop system such as that to be developed with the DeepU technology was also considered in the EHS in the context of potential environmental impacts with long term operation and abandonment, based on the detailed analyses of the laboratory results completed as part of WP3 of the project which have comprehensively reviewed the petrophysical characteristics of the well bore achieved through drilling with the laser at laboratory scale. It is important to note however, that such testing and experiments are still ongoing and that a further update of the EHS will be required at later stages of the project.

The EHS risk assessment completed as part of this task has focussed on the following key processes associated with DeepU:

- General Heat and Safety Procedures
- Drilling operations
- Laser Operational procedures
- Supercritical Gas Flushing System
- DeepU HE Completion
- Operational Phase of the closed loop system and
- Environmental considerations

A hazard assessment has been completed against the above categories for the processes associated with the processes against the above categories where risk targets (persons, environment, others) have been defined. The risk profile for each of the hazards has been classified and scored based on the risk matrix shown in table 3 below.

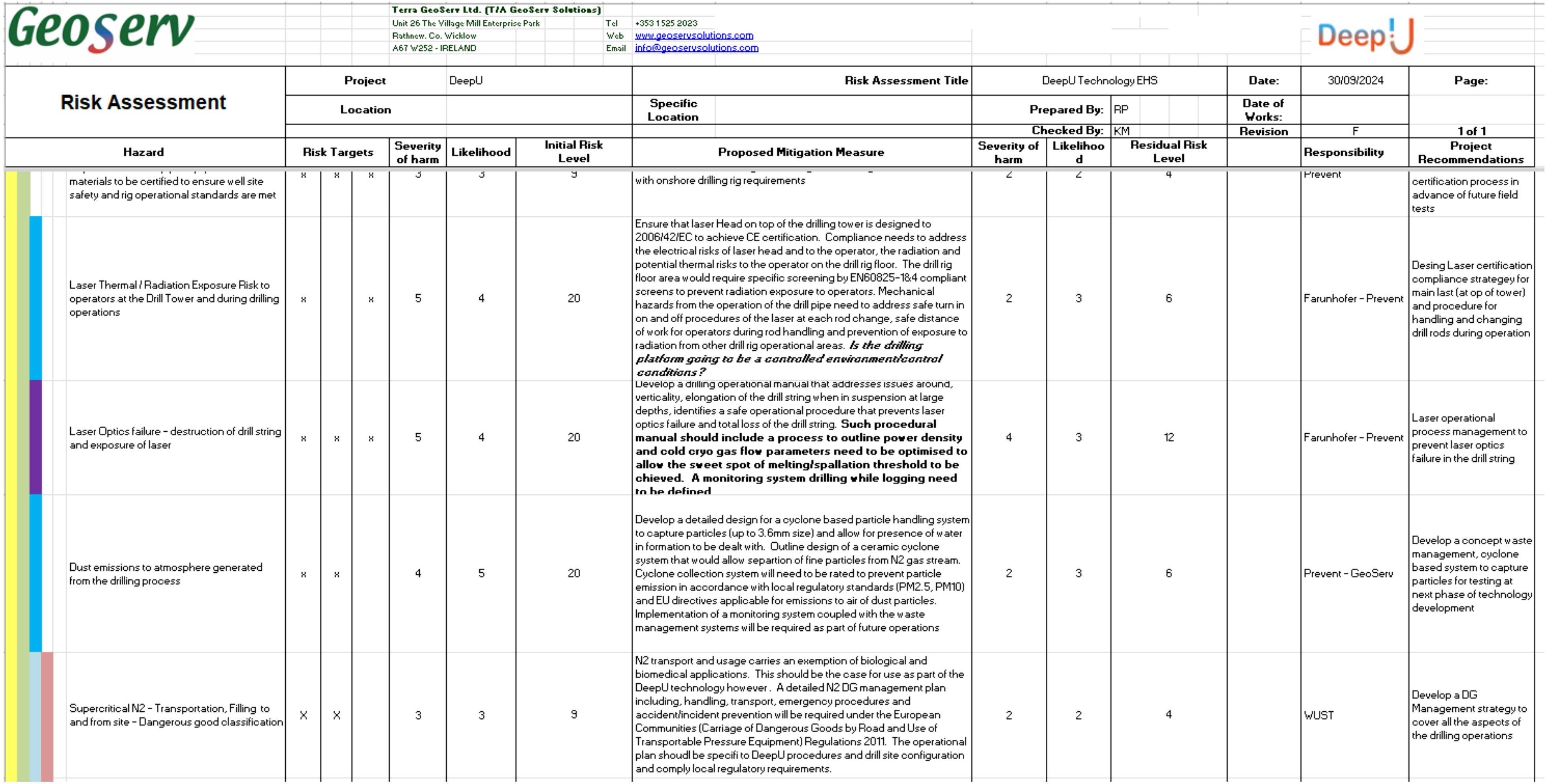
The outcome of the risk assessment process is shown in table 4. This outlines the risk rating of the initial hazards identified and proposes mitigations measures (at the time of writing this deliverable) which are being implemented by the project partners as part of the ongoing technology development. An example for the EHS Risk Assessment is shown in table 4 of this public deliverable, however, the full content is reserved for deliverable D4.3.

It is recognised that the EHS RA and the outcomes of the Technology Roadmap are still under development and are likely to continue evolving throughout the subsequent months of the project. The content of the EHS will, therefore, likely require updating and modification as the project evolves.

Table 3 - DeepU EHS Risk Assessment Matrix Scoring

			Consequence				
Risk Assessment			**Negligeable (1)**	**Minor (2)**	**Moderate (3)**	**Major (4)**	**Catastrophic (5)**
		People	Local treatment with short recovery - minor short term health effects.	Medical treatment required or short term acute health effects.	Lost Time Injury (off work recovery required) or short / medium term health issues.	Extensive injuries or chronic health issues.	Single fatality or permanent disability.
		Environment	Onsite release, containable with minimal damage. Localised impact only.	Major onsite release with some damage, no offsite damage. Numerous and/or widespread but small scale impacts on energy and waste. Remediation in terms of days..	Offsite release, no significant environmental damage. Remediation in terms of weeks.	Major offsite release, short to medium term environmental damage. Remediation in terms of months.	Major offsite release, long term environmental damage. Remediation in terms of years.
		Others	Workforce concern	Local community concern	Regional concern	Widespread reputation loss to single business unit, widespread community outcry.	Widespread reputation loss to more than one business unit, extreme community outcry nationally.
Determine the Likelihood	5	**Almost certain**	**Medium**	**High**	**Very High**	**Very High**	**Very High**
	4	**Likely**	**Medium**	**Medium**	**High**	**Very High**	**Very High**
	3	**Possible**	**Low**	**Medium**	**Medium**	**High**	**Very High**
	2	**Unlikely**	**Low**	**Low**	**Medium**	**Medium**	**High**
	1	**Rare**	**Low**	**Low**	**Low**	**Medium**	**Medium**

Table 4 - DeepU EHS Risk Assessment and proposed mitigation measures



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Risk Assessment

Project DeepU
Risk Assessment Title DeepU Technology EHS
Date: 30/09/2024
Page: 1 of 1
Location
Specific Location
Prepared By: RP
Date of Works:
Checked By: KM
Revision F

Hazard	Risk Targets			Severity of harm	Likelihood	Initial Risk Level	Proposed Mitigation Measure	Severity of harm	Likelihood	Residual Risk Level		Responsibility	Project Recommendations
materials to be certified to ensure well site safety and rig operational standards are met	x	x	x	3	3	9	with onshore drilling rig requirements	2	2	4		Prevent	certification process in advance of future field tests
Laser Thermal / Radiation Exposure Risk to operators at the Drill Tower and during drilling operations	x		x	5	4	20	Ensure that laser Head on top of the drilling tower is designed to 2006/42/EC to achieve CE certification. Compliance needs to address the electrical risks of laser head and to the operator, the radiation and potential thermal risks to the operator on the drill rig floor. The drill rig floor area would require specific screening by EN60825-1&4 compliant screens to prevent radiation exposure to operators. Mechanical hazards from the operation of the drill pipe need to address safe turn in on and off procedures of the laser at each rod change, safe distance of work for operators during rod handling and prevention of exposure to radiation from other drill rig operational areas. ***Is the drilling platform going to be a controlled environment/control conditions?***	2	3	6		Farunhofer - Prevent	Desing Laser certification compliance strategey for main last (at op of tower) and procedure for handling and changing drill rods during operation
Laser Optics failure - destruction of drill string and exposure of laser	x	x	x	5	4	20	Develop a drilling operational manual that addresses issues around, verticality, elongation of the drill string when in suspension at large depths, identifies a safe operational procedure that prevents laser optics failure and total loss of the drill string. **Such procedural manual should include a process to outline power density and cold cryo gas flow parameters need to be optimised to allow the sweet spot of melting/spallation threshold to be chieved. A monitoring system drilling while logging need to be defined**	4	3	12		Farunhofer - Prevent	Laser operational process management to prevent laser optics failure in the drill string
Dust emissions to atmosphere generated from the drilling process	x	x		4	5	20	Develop a detailed design for a cyclone based particle handling system to capture particles (up to 3.6mm size) and allow for presence of water in formation to be dealt with. Outline design of a ceramic cyclone system that would allow separtion of fine particles from N2 gas stream. Cyclone collection system will need to be rated to prevent particle emission in accordance with local regulatory standards (PM2.5, PM10) and EU directives applicable for emissions to air of dust particles. Implementation of a monitoring system coupled with the waste management systems will be required as part of future operations	2	3	6		Prevent - GeoServ	Develop a concept waste management, cyclone based system to capture particles for testing at next phase of technology development
Supercritical N2 - Transportation, Filling to and from site - Dangerous good classification	X	X		3	3	9	N2 transport and usage carries an exemption of biological and biomedical applications. This should be the case for use as part of the DeepU technology however. A detailed N2 DG management plan including, handling, transport, emergency procedures and accident/incident prevention will be required under the European Communities (Carriage of Dangerous Goods by Road and Use of Transportable Pressure Equipment) Regulations 2011. The operational plan shoudl be specifi to DeepU procedures and drill site configuration and comply local regulatory requirements.	2	2	4		WUST	Develop a DG Management strategy to cover all the aspects of the drilling operations

7 TECHNOLOGY ROADMAP FOR DEEPU DEVELOPMENT

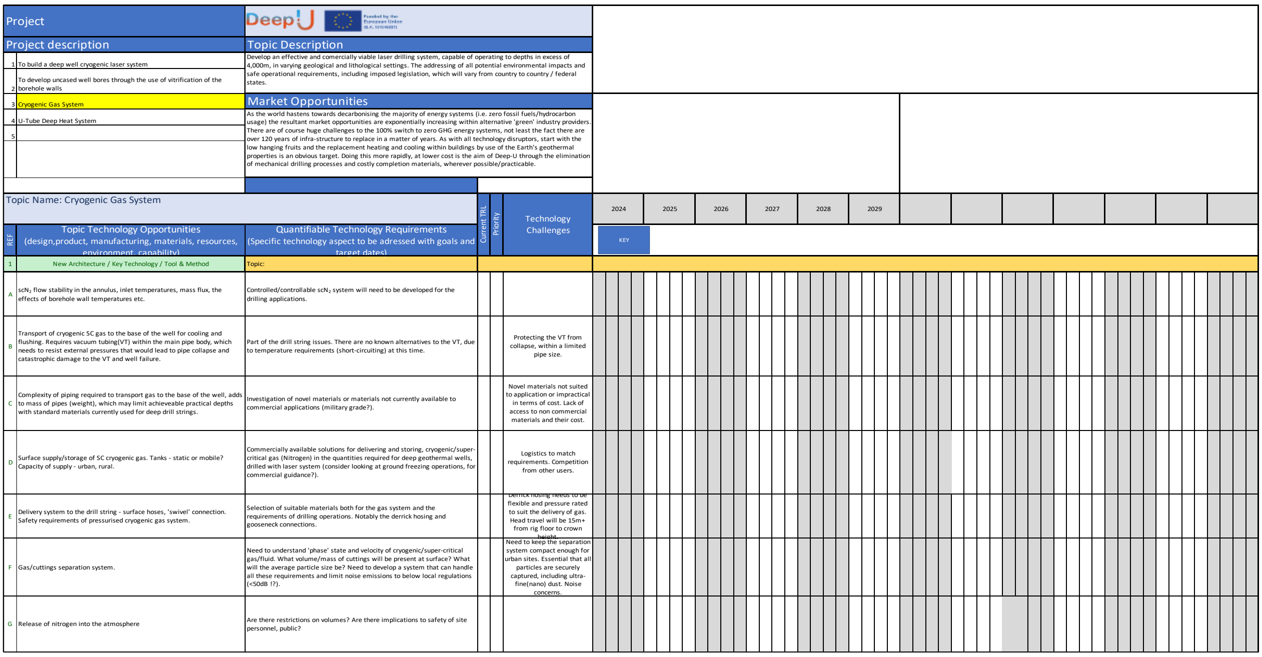
Technology Roadmaps are commonly used when developing innovative and challenging methodologies to solve problems that are currently not addressed. It allows for the integration of both tangible products and the processes required to realise successful outcomes and the hurdles that need to be cleared.

There are three main issues that a Technology Roadmap goes a long way to help address:

- It details the needs, and the technologies required to meet those needs and help reach a consensus, and
- Provides a visual mechanism to assist with forecasting the technological developments, and
- Assists with coordinating each of the technology developments.

The DeepU project is centred around utilizing existing technologies in novel ways and developing ground-up technologies to allow the system to function within a drilling site environment, hence why a robust technology roadmap is so important and a document that will be constantly evolving throughout the project lifetime and beyond. An extract of such roadmap is shown in table 5 below.

Table 5 – Extract of DeepU Technology Roadmap



Project	
Project description	**Topic Description**
1 To build a deep well cryogenic laser system	Develop an effective and comercially viable laser drilling system, capable of operating to depths in excess of 4,000m, in varying geological and lithological settings. The addressing of all potential environmental impacts and safe operational requirements, including imposed legislation, which will vary from country to country / federal states.
2 To develop uncased well bores through the use of vitrification of the borehole walls	
3 Cryogenic Gas System	**Market Opportunities**
4 U-Tube Deep Heat System	As the world hastens towards decarbonising the majority of energy systems (i.e. zero fossil fuels/hydrocarbon usage) the resultant market opportunities are exponentially increasing within alternative 'green' industry providers. There are of course huge challenges to the 100% switch to zero GHG energy systems, not least the fact there are over 120 years of infra-structure to replace in a matter of years. As with all technology disruptors, start with the low hanging fruits and the replacement heating and cooling within buildings by use of the Earth's geothermal properties is an obvious target. Doing this more rapidly, at lower cost is the aim of Deep-U through the elimination of mechanical drilling processes and costly completion materials, wherever possible/practicable.
5	

Topic Name: Cryogenic Gas System

REF	Topic Technology Opportunities (design,product, manufacturing, materials, resources, environment, capability)	Quantifiable Technology Requirements (Specific technology aspect to be adressed with goals and target dates)	Current TRL	Priority	Technology Challenges	2024	2025	2026	2027	2028	2029
						KEY					
1	New Architecture / Key Technology / Tool & Method	Topic:									
A	scN_2 flow stability in the annulus, inlet temperatures, mass flux, the effects of borehole wall temperatures etc.	Controlled/controllable scN_2 system will need to be developed for the drilling applications.									
B	Transport of cryogenic SC gas to the base of the well for cooling and flushing. Requires vacuum tubing(VT) within the main pipe body, which needs to resist external pressures that would lead to pipe collapse and catastrophic damage to the VT and well failure.	Part of the drill string issues. There are no known alternatives to the VT, due to temperature requirements (short-circuiting) at this time.			Protecting the VT from collapse, within a limited pipe size.						
C	Complexity of piping required to transport gas to the base of the well, adds to mass of pipes (weight), which may limit achieveable practical depths with standard materials currently used for deep drill strings.	Investigation of novel materials or materials not currently available to commercial applications (military grade?).			Novel materials not suited to application or impractical in terms of cost. Lack of access to non commercial materials and their cost.						
D	Surface supply/storage of SC cryogenic gas. Tanks - static or mobile? Capacity of supply - urban, rural.	Commercially available solutions for delivering and storing, cryogenic/super-critical gas (Nitrogen) in the quantities required for deep geothermal wells, drilled with laser system (consider looking at ground freezing operations, for commercial guidance?).			Logistics to match requirements. Competition from other users.						
E	Delivery system to the drill string - surface hoses, 'swivel' connection. Safety requirements of pressurised cryogenic gas system.	Selection of suitable materials both for the gas system and the requirements of drilling operations. Notably the derrick hosing and gooseneck connections.			Derrick hosing needs to be flexible and pressure rated to suit the delivery of gas. Head travel will be 15m+ from rig floor to crown height.						
F	Gas/cuttings separation system.	Need to understand 'phase' state and velocity of cryogenic/super-critical gas/fluid. What volume/mass of cuttings will be present at surface? What will the average particle size be? Need to develop a system that can handle all these requirements and limit noise emissions to below local regulations (<50dB !?).			Need to keep the separation system compact enough for urban sites. Essential that all particles are securely captured, including ultra-fine(nano) dust. Noise concerns.						
G	Release of nitrogen into the atmosphere	Are there restrictions on volumes? Are there implications to safety of site personnel, public?									

The outcomes of the technology roadmap are feeding into the final recommendation in Task 4.3 that will identify critical process management solutions to be achieved in order for DeepU to gain compliance and achieve commercialisation at later stages of development.

An example for the technology roadmap is shown in table 5 of this public deliverable, however, the full content of the roadmap is reserved for deliverable D4.3.

8 CONCLUSIONS & RECOMMENDATIONS

An extensive review of Health, Safety and Environmental practices was considered as part of this deliverable in the context of the operational procedures associated with the use and development of the DeepU drilling system.

FMEA

- The FMEA is a live document that analyses potential failure(s) of system components and operational procedures, the probability of the failure occurring and the effects it will have upon the entire operation.
- The FMEA will be constantly updated as the system progresses through each iterative stage.

Health & Safety

- Generally accepted health and safety practices will be adopted. Such practices will require to be adapted from existing H&S processes which are applied in the industrial sector for the use and operation of industrial lasers and cryogenics, to develop a process H&S workflow specific to that applicable to the operational procedures and requirements associated with a deep drill site.
- The environmental, licensing and site-specific requirements (including planning consents and licencing) associated with the completion of the deep borehole and geothermal projects are being considered as part of the mitigation measures and the findings and results of testing of the laser drilling method developed by DeepU. The initial outcomes of the assessment suggest that conventional drilling and completion methods may need to be applied as part of the initial part of any DeepU laser drilling project in order to comply with environmental regulations and reduce any risks of long term operation of the system. A detailed process associated with this well completion is being developed as part of the final phases of the project.
- Specific health and safety requirements for the operational procedures of the DeepU drilling and completion process are being developed based on the outcomes of the FMEA and the EHS risk assessment. These requirements are intrinsically linked to the design of the drilling equipment and the cryogenic gas handling and particle collection system. Both of these require to achieve compliance with existing regulatory frameworks for deep drilling operations. A process safety management hierarchy for the different competent is being considered based on the outcomes of the FMEA and the EHS risk assessment and being developed as part of the recommendations of the project.
- The completion of additional design of the drilling components and the results of further testing demonstrating the well bore completion strategy with DeepU will require for further environmental impact assessment to be undertaken at a later phase of development to ensure that additional risks can be prevented by putting in place adequate detection and control measures during the drilling operations and long term operation of the DeepU boreholes.

Regulatory Acceptance

- The DeepU system will have to gain full regulatory acceptance from a recognised standards authority (e.g. DNV; International Association of Drilling Contractors) as well as meeting regional, national and global requirements (e.g. CE marking, Health and Safety at Work acts).

- The completion of the different system components including the drill string will differ from current drilling equipment standards and, due to the use of vacuum tubing and specialised connections required, this will be more aligned with Pressure Equipment Directive specifications. This will require the drill string to be certified and accepted by different regulatory bodies for use on drill sites.
- Acceptance of regulatory bodies will also be required for using industrial lasers on a drill site and hence the development of detailed operational procedures which combine the use of such lasers with the use of a cryogenic gas flushing system will need to be developed. Consultation with regulatory bodies, demonstrating robust EHS and OHS procedures will need to take place once the DeepU drilling process components are further integrated and made specific to a drilling site.

9 REFERENCES

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Appendix A – FMEA

Funded by the European Union
(G.A. 101046937)

Deep-U FMEA

Process/Product Name: Cryogenic Gas
Responsible: Geoserv

Prepared By: Kevin Mallin
FMEA Date (Orig.): 10/02/2023 (Rev.): 08/11/2024

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls / Detection	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Cryogenic Gas Delivery to drill site.	*No gas available*	*Drilling Stops*	*9*	*Poor management failing to order adequate gas supplies or poor supply-chain management*	*7*	*Supply chain management processes.*	*6*	*378*	*Robust supply chain management and communications.*	*Procurement team, site operations team*	*To be defined*	*9*	*7*	*6*	*378*
Change over from one supply source to another	Leakage, delivery pipe issues,	Risk to personnel, Risks to equipment, Environmental impacts	9	Poor training of site operators. Poor HAZOPS planning Non-compliant equipment.	5	HS&E Requirements. Incident reporting requirements. Accident recording.	5	*225*	Robust Risk Assessments and adherence to Method Statements. Monitoring and recording.	*Site personnel, supervisors and continuous training programmes.*	To be defined	9	5	5	225
Delivery hose from tank to rig	Hose rupture. Connections fail	Large discharge of cryogenic gas, with risk to personnel and equipment / environment.	10	Poor maintenance/training. Inadequate safety procedures.	2	Proscribed inspections of equipment. Regular training and assessment of personnel.	2	*40*	Rigorous testing and maintenance procedures	*HS&E Director, Site supervisors, Site personnel.*	To be defined	10	2	2	40
Rotary cryogenic swivel	Seal leaks, embrittlement of swivel components.	Cessation of drilling. Extensive damage to rig equipment and superstructure. Possible major failure of mast, leading to personnel risks.	10	Inadequate design or lack of understanding of the equipment interaction between tank supply and injection into the drill string.	2	None	10	*200*	Rigorous design procedures, peer reviews and testing. Selection of materials suited to the tasks required.	*PREVENT*	To be defined	10	2	10	200
								0							0
Cryogenic Gases within drill pipe.	Poor sealing between tool joints.	Pipe body embrittlement. Loss of circulation and damage to laser.	10	Poor design criteria. Ungauged operational wear.	8	None	10	*800*	Rigorous design and testing of tool joint connections. Set criteria for identifying and monitoring wear of tool joints that might lead to failure.	*PREVENT*	To be defined	10	8	10	800
Insufficient gas volume to carry residual cuttings to the surface.	Cuttings fail to exit borehole, vitrified material results in 'clinker' build up in the well.	Stuck pipe, loss of well.	10	Miscalculation of required gas volume or failure to deliver suffi cient gas to the bottom of the well.	10	Mathematical modelling, laboratory testing. Empirical results from other gas (air) drilling operations. Lack of cuttings exiting well as predicted from rock volume and laboratory testing.	6	*600*	Diligent modelling and rigorous testing. Volumetric flow recording at wellhead and measurement of mass of cuttings ejected from well, compared to models.	*PREVENT. FRAUNHOFER. GEOSERV.*	To be defined	10	10	6	600
Large volumes of gas being emitted	Reduction in available air for normal respiratory function of personnel.	Major Health and Saftey Issues. Shut down of operation.	10	Lack of monitoring. Poor ventilation. Inadequate design of surface equipment.	8	Safe working guidelines from Cryogenic Gas suppliers and legislation. Checks to ensure current measures are applicable to drilling operations.	6	*480*	Engagement with cryogenic gas experts and suppliers. Full review of surface operations.	PREVENT FRAUNHOFER GEOSERV THIRD-PARTIES	To be defined	10	8	6	480
Gas/Cuttings/ Dust separation.	Fine dust being suspended in flushing gas, could cause issues for personnel and environment.	Operations will be stopped while issue is resolved	10	Poor surface management of returning flush gas and cuttings.	9	Air drilling will present the same problems, although the nature of suspended solids in the flush gas may be different. Separators and filtration.	7	*630*	A thorough understanding of the issues, including gas characteristics, volume and PSD of cuttings, current separation technologies.	PREVENT FRAUNHOFER GEOSERV THIRD-PARTIES	To be defined	10	9	7	630
`Water/Gas Separation	Formation fluids, vapourised during operations will condense at surface.	Dust clogging in separator. Issues with produced waters and containment.	10	Formation fluids being vapourised by temperature of laser/rock.	10	None	10	###	To be defined	Consortium	To be defined	10	10	10	###
Condensing of formation fluids within wellbore	Reduction in temperatue of water vapour may cause condensation and 'mud-cake' build up on virified wall.	Reduced or loss of returns/ circulation due to mud rings forming. Stuck pipe / loss of drill string.	10	Insufficient uphole velocity of gas flush and cuttings. Drop in wellbore temperature causing water vapour to condense.	10	None	10	###	To be defined	Consortium	To be defined	10	10	10	###
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Funded by the European Union (G.A. 101046937)

Deep-U FMEA

Process/Product Name: Drill String Components
Responsible: Geoserv

Prepared By: Kevin Mallin
FMEA Date (Orig.): 10/02/2023 (Rev.): 08/11/2024

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls / Detection	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Drill Pipe outer body material	*Not accepted by drilling community, unless they conform to current standards (eg S135)*	*No market penetration through existing contractors*	*10*	*Insufficient market knowledge.*	*8*	*Market engagement*	*8*	*640*	*Full market appraisal and engineered solution for the drill pipe outer body material.*	*Prevent*	*To be defined*	*10*	*8*	*8*	*640*
Tool joint body material not standard or accepted by industry	Lack of uptake by industry	No market penetration through existing contractors	10	Poor market research or lack of engagement	8	Industry standards and regulations (eg API / IADC)	8	*640*	Stakeholder engagement to establish new industrial standards.	Consortium	To be defined	10	8	8	*640*
Friction welding of tool joints and pipe bodies.	Internal 'Ram Horns' due to RFW process.	Unable to install inner pipes (laser, gas) due to internal 'Ram Horns' / Swarf	10	Rotary Friction Welding process and no internal wiping of 'Ram Horns'	9	Quality controls and post RFW inspections.	7	*630*	Establish QC regime suited to the manufacture of Laser Drilling outer pipes.	*Prevent*	Manufacturing process to ensure that internal obstructions are mitigated for.	10	9	7	*630*
Tool joint configuration and comparative standards	Lack of acceptance by industry	Slow uptake of technology, wholesale changes to rig structures	10	Lack of planning to integrate with current industry standards	10	API and IADC tool joint standards	5	*500*	Integrating tool joint standards to monitor and measure new and wear limits	*Consortium*	Tool joints will be manufactured to current API standards.	10	10	5	*500*
Tool Joint Quality Assurance and inspection processes	No Industry standard	Loss of control, track and trace.	10	Lack of adoption of standards	8	None	10	*800*	Early-stage understanding of current tool joint standards and how the Laser Drilling pipes can adapt/adopt/ integrate	*Consortium*	To follow API inspection standards.	10	8	10	*800*
Supply chain issues for special cryogenic gas delivery inner pipes (316L).	Poor availability of drill pipes which will affect project delivery prospects	Severe. New technologies have to prove themselves very quickly from the outset or risk low market penetration.	10	Geo-Political risks that can impinge on global supply chains. Unforeseen or poorly planned scenarios (pandemics/conflicts).	10	Machine Learning & Artificial Intelligence that can better track and predict supply chain issues. Blockchain procurement system(s)	4	*400*	Selecting materials & components that are readily available. Develop a robust supply-chain and make use of modern procurement software (ML/AI/BC)	*Third party specialists.*	Included in design criteria, to minimise issues.	10	10	4	*400*
Pipe elongation due to free hanging in borehole.	Damage to laser head. Bouncing of pipe running in/out of hole - shock to jool joints.	damage of laser haed. Loss of drill string.	10	Poor handling of drill pipe when running. Failing to slow down pipe to minimise shock strain and exceeding pipe yield.	8	Stringent handling procedures. Drill head sensors that monitir distance between bottom of hole and drill head.	8	*640*	Advanced sensor system. Modelling of drill pipe stretch to evaluate risk.	*PREVENT, Geoserv, pipe manufacturers*	To be advised	10	8	8	*640*
Drill string alignment to maintain laser strightness	Sudden buckling/bending of drill string	Catastrophic. Laser would burn through pipe	10	Poor drilling practices	8	None at present	10	*10*	Detailed handling/drilling procedures. Method to maintain laser remains central at all times.	Fraunhofer, PREVENT	Internal re-focusing mirrors.	10	8	10	800
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Funded by the European Union
(G.A. 101046937)

Deep-U FMEA

Process/Product Name: Unconsolidated formations / Drift

Responsible: Geoserv

Prepared By: Kevin Mallin

FMEA Date (Orig.): 10/02/2023 (Rev.): 08/11/2024

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls / Detection	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Backfill waste	*Deposits may containg volatile chemicals, toxins and pathogens, that cannot be safely penetrated with the laser*	*Site activities stopped under Health and Safety legislation concers.*	*10*	*Inadequate pre-drilling assessments.*	*8*	*Full and thorough pre-drilling site appraisal, including desk studies, trial excavations, sampling and testing.*	*8*	*640*	*Full and thorough pre-drilling assessment. Installation of conductor pipe(casing) to eliminate risk and satisfy health and safety.*	*Site operator*	*TBC*	*10*	*8*	*8*	*640*
Buried services (utilities)	High temperature from laser will seriously damage any buried services within range.	Site activities stopped. Serious community impacts. Risks to site personnel.	10	Inadequate planning or poor buried services record. Lack of engagement with statutory authorities and service providers.	9	Engagement with statutory authorities/service providers. Buried services mapping and location. Hand-dug pits, effective for shallow services only.	6	*540*	Engagement with service providers. Pre-drilling excavations and installation of conductor casing.	Site operator	TBC	10	9	6	*540*
Unconsolidated drift deposits.	Inability for the laser to penetrate / vitrefy granular materials	Damage to laser head.	10	Poor planning of shallow sub-surface prognoses.	8	Comprehensive desk studies. Shallow geophysics (GPR). Trial pits, shallow investigation holes, in-situ testing, Lab testing.	7	*560*	Comprehensive early stage planning and ground investigation techniques	*Site operator*	TBC	10	8	10	*800*
Steel casing installed to alleviate problems listed above.	Heat generated by laser and cryogenic cooling may cause severe damage to casing and trap laser head	Loss of hole. Trapped/lost drill string	10	Proximity of laser head to casing shoe.	10	No known current controls	10	*1000*	Laboratory testing, field tseting.	*Prevent / IAPT*	TBC	10	10	10	*1000*
Saturated clays	Laser desicates clays and bakes them in place.	Unable to penetrate and advance borehole	10	Heat from laser transforms clays, but does not vapourise them - bakes them in place	10	No known current controls	10	*1000*	Laboratory testing.	*Prevent/IAPT/UNIPD*	TBC	10	10	10	*1000*
Shallow soil gases	Gas generated from organic decay at shallow depth or migration from depth	Explosion risk from heat of laser. Danger to personnel, equipment, community. Operations halted.	10	Organic gases collect in shallow porous formations, butr cannot naturally vent to atmosphere	10	Shallow gas monitoring wells. Venting wells.	4	*400*	Any potentila sites include shallow gas monitoring wells to be installed for a minimum of 12 weeks prior to main drilling.	*Site operator*	TBC	10	10	4	*400*
Volatile chemicals present in shallow deposits. Leachates, spillages.	Fire, explosion from heat of laser	Explosion risk from heat of laser. Danger to personnel, equipment, community. Operations halted.	10	Post industrial, brownfield sites in developed areas. Poor planning and investigations	8	Ground investigations, including desk top studies, trial pits, boreholes. Soil and water sampling. Chemical testing.	7	*560*	Comprehensive pre main drilling operations, site study, sampling and testing.	*Site operator*	TBC	10	8	7	*560*
Drift / weathered rock interface	Fractured rock, weathered rock, perched water, laser creates melted formation.	Lost time, wellbore instability, steam flash.	10	Later drift deposits sitting on top of wetahred rock. Meteoric water trapped in interface layer. Particular issues in near marine, fluvial and glacieted regions.	10	Ground investigations, including desk top studies, trial pits, boreholes. Soil and water sampling. Chemical testing.	5	*500*	Comprehensive pre main drilling operations, site study, sampling and testing. Casing installed into competent rock, prior to main drilling	Site operator	TBC	10	10	5	500
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Deep-U FMEA

Process/Product Name: Sedimentary Formations (Clastic and non-Clastic)

Responsible: Geoserv

Prepared By: Kevin Mallin

FMEA Date (Orig.): 10/02/2023 (Rev.): 08/11/2024

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls / Detection	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Pore spaces fully saturated.	*Flash steam, no control of fluid pressure.*	*Loss of well. Wild well conditions, resulting in shut-down.*	*10*	*Sedimentary formations have high porosity, generally fully saturated with water. The high heat from the laser head will vaporise both rock and fluid. Pore fluids will flow into the wellbore.*	*10*	*As of yet, there is no known data to evaluate what will happen in such conditions.*	*10*	*1000*	*Laboratory tests that replicate in-hole conditions (pressure, saturation, pore space) and laser temperature*	*Prevent, IAPT, UNIPD*	*TBC*	*10*	*10*	*10*	*1000*
Pore spaces contain hydrocarbons	If porosity/ permeability are high, explosion risk or uncontrollable gas flows.	Loss of well. Wild well conditions, resulting in shut-down.	10	Deeper sedimentarty basins likely to contain hydrocarbons, under pressure.	5	For laser drilling, unknown, although Nitrogen gas will lower explosion risk. For mud drilling, hydrostatic pressure of drilling fluid. Vitrification of borehole may prevent gas ingress?	8	*400*	Modelling of laser interaction with sedimentary rocks. Advanced laboratory testing on pressured cores.	UNIPD	TBC	10	5	8	*400*
Fractured, faulted formations.	High permeability zones, containg fluids or gases. Steam flashes, explosion risk, uncontrollable flows.	Loss of well. Wild well conditions, resulting in shut-down.	10	Sedimentary basins, subjected to fracture pressures and faulting. Varying levels of deposition/solubility may lead to large voids (Karstic).	10	Offset well data, geophysics.	8	*800*	Further study and evaluation of laser drilling suitability, in such formations.	*Consortium members.*	TBC	10	10	8	*800*
Fractures infilled with clay deposits	Dessication of clays/minerals that may prevent the laser from advancing. Damage to laser head.	Laser drilling has to stop.	10	Clay infill, which may be random	10	No effective detection/control measures, currently.	10	*1000*	Greater understanding of how the laser will interact with clays/clay minerals and formulate / evaluate mitigation strategies.	*Consortium members.*	TBC	10	10	10	*1000*
Non-clastic formations do not vaporise in a controlled way.	Varying mineral content affect the vaporise process.	Well progress halted, well profile not suitable for Deep-U heat exchanger.	10	Mineral content variations and reaction to high temperatures.	10	None at present.	10	*1000*	Further research and testing.	*Consortium members.*	TBC	10	10	10	*1000*
Clastic formations with high silica content, may result in reflective surfaces that damage the laser head.	High silica content might result in flow, rather than vaporisation.	Damage to laser head. Wellbore lost.	10	High silicate content and pore space.	10	None at present.	10	*1000*	Further research and testing.	*Consortium members.*	TBC	10	10	10	*1000*
High temperature from laser.	High temperatures cause physical impacts on near wellbore formations.	Geomechanical failures.	10	This is yet to be determined, but thermal shock is a known issue in other areas of sub-surface exploitation.	8	None at present.	10	*800*	Further study and evaluation of laser drilling suitability, in such formations.	*Consortium members.*	TBC	10	8	10	*800*
Homogeneity of formations	Adverse reactions with cryogenic gas and pore gases.	Wellbore collapse. Loss of well	10	Pore gases expand beyond fracture gradient and implode the well bore.	10	None at present.	10	*1000*	Testing/modelling of different rock-types to ascertain the likely outcomes.	UNIPD	Continued testing	10	10	10	1000
Reaction of limestones to laser melting	Reflection of laser causing damage to head. Geomechanical failure of wellbore	Drilling stops. Loss of well bore	10	Excessive heat. Partial melting of formation.	10	None at present.	10	*1000*	Continued testing and modelling to evaluate and quantify issue.	UNIPD, Fraunhofer	Continued testing	10	10	10	1000
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Deep-U FMEA

Process/Product Name: Meta-Sedimentary formations

Responsible: Geoserv

Prepared By: Kevin Mallin

FMEA Date (Orig.): 10/02/2023 (Rev.): 08/11/2024

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls / Detection	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Pressure altered sediments of low particle size (<20 microns).	*Thermal fracture propogation. No viritification of wellbore wall. Instability of formation.*	*Loss of well. Stuck drill string. Drilling induced seismicity risk through reactivation of faults, as pore pressures change rapidly.*	*10*	*Sudden changes in lithologies. Unknown reactions to temperatures created by laser head and interaction of cryogenic gas.*	*10*	*No known controls exist.*	*10*	*1000*	*Petrogical testing and further understanding how these formations will respond to laser/cryogenic gas drilling.*	*UNIPD?*	*TBC*	*10*	*10*	*10*	*1000*
Heat and chemically altered sediments (Schists)	Sudden rise in formation temperature and pressure changes, may result in chemical and physical changes.	Loss of well. Stuck drill string. Unknown consequences.	10	Laser hit and cryogenic cooling.	10	No known controls exist.	10	*1000*	Petrological testing that include in-situ conditions (e.g. confining pressures)	UNIPD?	TBC	10	10	10	*1000*
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Severity Scale

Adapt as appropriate

Effect	Criteria: Severity of Effect	Ranking
Hazardous - Without Warning	May expose client to loss, harm or major disruption - failure will occur **without** warning	10
Hazardous - With Warning	May expose client to loss, harm or major disruption - failure will occur **with** warning	9
Very High	Major disruption of service involving client interaction, resulting in either associate re-work or inconvenience to client	8
High	Minor disruption of service involving client interaction and resulting in either associate re-work or inconvenience to clients	7
Moderate	Major disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	6
Low	Minor disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	5
Very Low	Minor disruption of service involving client interaction that does not result in either associate re-work or inconvenience to clients	4
Minor	Minor disruption of service not involving client interaction and does not result in either associate re-work or inconvenience to clients	3
Very Minor	No disruption of service noticed by the client in any capacity and does not result in either associate re-work or inconvenience to clients	2
None	No Effect	1

Occurrence Scale

Probability of Failure	Time Period	Per Item Failure Rates	Ranking
Very High: Failure is almost inevitable	More than once per day	>= 1 in 2	10
	Once every 3-4 days	1 in 3	9
High: Generally associated with processes similar to previous processes that have often failed	Once every week	1 in 8	8
	Once every month	1in 20	7
Moderate: Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions	Once every 3 months	1 in 80	6
	Once every 6 months	1 in 400	5
	Once a year	1 in 800	4
Low: Isolated failures associated with similar processes	Once every 1 - 3 years	1 in 1,500	3
Very Low: Only isolated failures associated with almost identical processes	Once every 3 - 6 years	1 in 3,000	2
Remote: Failure is unlikely. No failures associated with almost identical processes	Once Every 7+ Years	1 in 6000	1

Detection Scale

Detection	Criteria: Likelihood the existence of a defect will be detected by process controls before next or subsequent process, -OR- before exposure to a client	Ranking
Almost Impossible	No known controls available to detect failure mode	10
Very Remote	Very remote likelihood current controls will detect failure mode	9
Remote	Remote likelihood current controls will detect failure mode	8
Very Low	Very low likelihood current controls will detect failure mode	7
Low	Low likelihood current controls will detect failure mode	6
Moderate	Moderate likelihood current controls will detect failure mode	5
Moderately High	Moderately high likelihood current controls will detect failure mode	4
High	High likelihood current controls will detect failure mode	3
Very High	Very high likelihood current controls will detect failure mode	2
Almost Certain	Current controls almost certain to detect the failure mode. Reliable detection controls are known with similar processes.	1