GEODRILL

Project acronym:	**Geo-Drill**		
Project title:	Development of novel and Cost-Effective drilling technology for geothermal Systems		
Activity:	LCE-07-17-Renewables		
Call:	H2020-LC-SC3-2018-RES-TwoStages		
Funding Scheme:	RIA	**Grant Agreement No:**	815319
WP1	**Requirement analysis and KPIs**		

D1.1

Due date:	31/07/2019	
Actual Submission Date:	30/07/2019	
Lead Beneficiary:	TVS	
Dissemination Level[1]:	PU	
Nature:	Report	
Status of this version:		**Draft under Development**
		For Review by Coordinator
	X	**Submitted**
Version:	V1	
Abstract	This deliverable reports on the failure mode and effects analysis (FMEA) of common failures in geothermal drilling.	

REVISION HISTORY

Version	Date	Main Authors/Contributors	Description of changes

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No. 815319

[1] Dissemination level security:

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

RE – Restricted to a group specified by the consortium (incl. Commission services) / **CO** – confidential, only for members of the consortium (incl. Commission services)

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1 EXECUTIVE SUMMARY

There are numerous components within the drill string that require protection/strengthening from the surrounding environment encountered and created during drilling for harnessing energy from geothermal fluid. The form of protection/strengthening varies depending on the properties of the geofluid and lithology of the sub-surface at each depth. Drill string breakage and tools failure due to fatigue, vibration, abrasion, erosion and corrosion are common but significantly important issues encountered in geothermal well drilling. These problems can result in risk and economic loss due to reduced rate of penetration (ROP) and increased non-productive time (NPT), and even loss of well/hole. Minimization or even eradication of these occurrences can therefore reduce the need for frequent trips to change bits/components and subsequently, a significant decrease in the cost of drilling the well(s).

To determine where the main focus should be for protective/strengthening solutions in this environment, failure mode and effects analysis (FMEA) has been carried out, rating failure modes to produce a ranking that reveals the most crucial components. This document provides the combined FMEA results collated and reviewed by expert in this field. It describes the nature of FMEA and its effectiveness in categorizing and prioritizing failure modes for deep geothermal drilling. The Geo-Drill hammer, with its improved rate of penetration (ROP), will aggravate the working conditions of the downhole drilling tools. Hence, to get the best out of the Geo-Drill hammer and drill string sensors, will require strengthening of drill string components such as the drill bit, drill collar etc. Understanding the failure modes of drill string components is therefore essential. The results of the FMEA are intended to be used to support and further determine the applicability of using the novel technologies developed in this project to reduce geothermal well drilling cost by increasing the rate of penetration (ROP) and by improving component life, thereby reducing the need of tripping (process of pulling the entire drill string).

The collated information shows that the failure modes (e.g., fatigue, vibration, abrasion, erosion and corrosion) influenced components in all the plants although the degree of effects varies with different subsurface lithology and fluid properties. A very brief summary of the FMEA is given below:

- All the failure modes being focused on are linked to severe cases in the system.
- The most critical case occurs in drill bit insert wear due to erosion.
- There are numerous components which could potentially benefit from the use of more erosion resistant material including the drill bit, hammer, drill pipe, drill collar, drill stabiliser etc.

The results from the FMEA support the fact that fatigue, vibration, abrasion, erosion and corrosion resistant solutions are needed for the drill string in geothermal well drilling tools. It also provides an excellent basis to estimate the effect such solutions would have on the system.

2 OBJECTIVES MET

This deliverable contributes towards the work package objective:

- To identify failure modes of geothermal drilling through FMEA analysis

3 FAILURE MODE AND EFFECT ANALYSIS (FMEA)

FMEA is a tool that is used to identify and prevent product and process failure before it occurs [1]. In this sense, failure can either refer to how a process or component fails (See figure 1 for wear of drill bit with usage), or to how its capability reduces, as will be done in this report. 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).

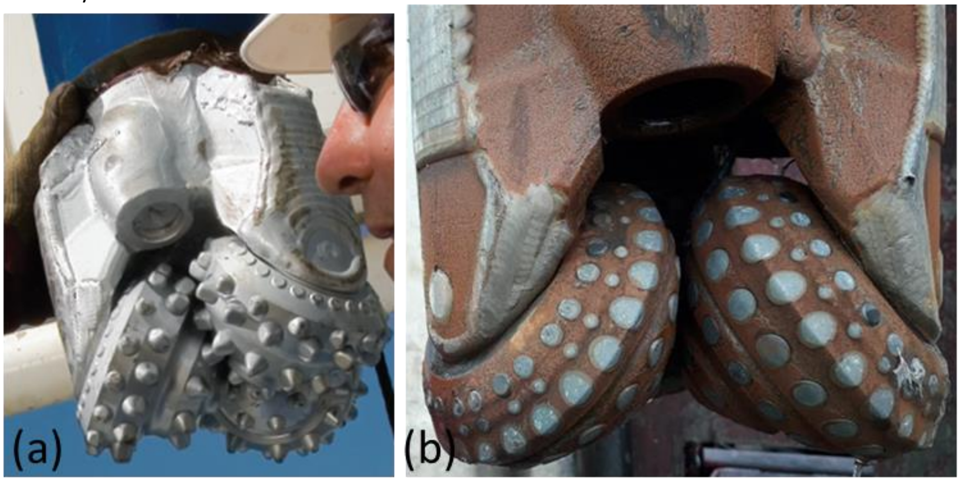

Figure 1: A typical example of wear of drill bit. (a) Before use, (b) Wear after 55.75 hrs of use. Drill fluid was water and air[†].

To perform a basic FMEA the failure mode, failure effect and failure cause have to be clear enough to rate the severity, occurrence and detectability appropriately. It is therefore imperative that the individuals filling out the FMEA have a good understanding of the functionality and effects damage can cause to the system. Once this has been identified and rated, the vales for S, O and D can be multiplied together to produce a risk priority number (RPN). This number can then be used as a method for identifying critical areas in the system. While this can be represented by the RPN value, this number can be misleading as it is highly reliant on the values for S, O and D, and views each of these with equal weight. To achieve more applicable results this number therefore has to be used in conjunction with other values to provide results that are more tailored to what is desired. Using the severity or occurrence value as extra criteria can provide such balance. Another method could be to use S*O as this removes the detectability factor and can therefore provide a more appropriate reference if the main focus is on the severity of a failure mode and its frequency. This value is used to analyse results from FMEA and is commonly referred to as the criticality of the failure mode [2]. FMEA can be used for a variety of industries as it is easily adapted to the environment through the specialised rating systems. This provides a basis to perform in-house analysis and comparison of systems but comparison between organisations is not possible unless the ranking scales being used are similar.

3.1 Geo-Drill Project and FMEA Analysis

The objective of the Geo-Drill project is to develop “holistic” drilling technologies that have the potential to drastically reduce the cost of drilling to large depths (5km or more) and at high temperatures (250^{0}C or more). Major innovations of the project are:

- A prototype 4 inch down-the-hole (DTH) mud hammer will be manufactured. Relevant parts will have the newly developed materials and coatings.
- A prototype drill monitoring system, with sensors mounted on the prototype DTH mud hammer, will be implemented
- Prototype drill bit buttons, with newly developed materials and coatings will be manufactured and implemented on several 5.25 inch drill bits
- Prototype tool joints and drill stabilisers will be manufactured with advanced materials and manufacturing technologies followed by integration on 3.5 inch drill pipes.
- Prototypes will first be tested and validated in laboratory environments, followed by full-scale testing and validation with the GZB drill rig.

[†] Source: Internet

As seen from the above list, the Geo-Drill project will develop an innovative DTH drilling hammer (See Figure 2). Before going into details, we have planned the FMEA study which will be an important step towards the development of the entire system. This study only focuses on the generic FMEA.

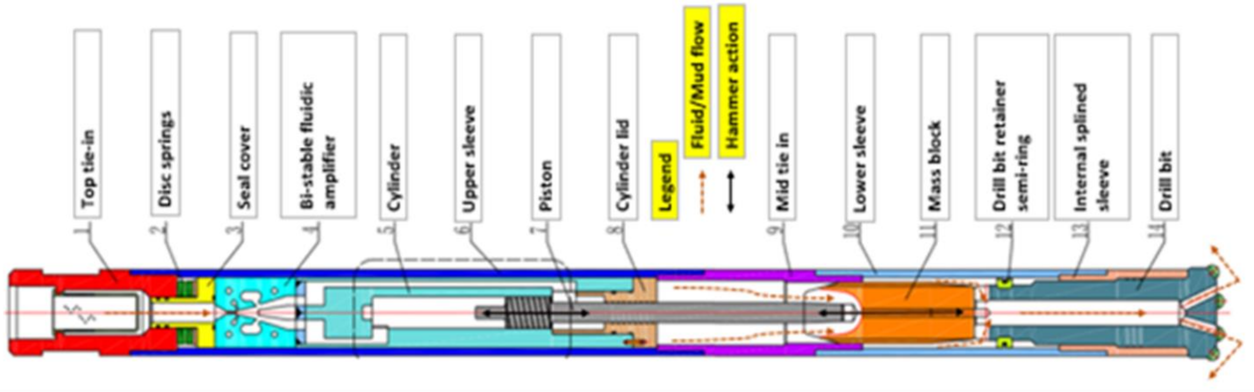

Figure 2: A Hammer with bi-stable fluidic oscillator. The picture shows some components of the Geo-Drill System. Sensor and energy systems will also be included in the system.

4 METHODS

The overall methodology of this FMEA study is shown in Figure 3. A brief explanation of each step of this analysis is given below:

Objective definition and analysis strategy development

The main objective of this study is to understand the potential failure modes, causes, effects and possible actions to recover the potential harmful effects for each part that is combined to make up the final Geo-Drill system. At the beginning of the study, TVS planned the following: extensive literature review, Geo-Drill system component listing, FMEA analysis template preparation, circulation of the template to the consortium members, compilation of feedback from the members and finalisation of the study.

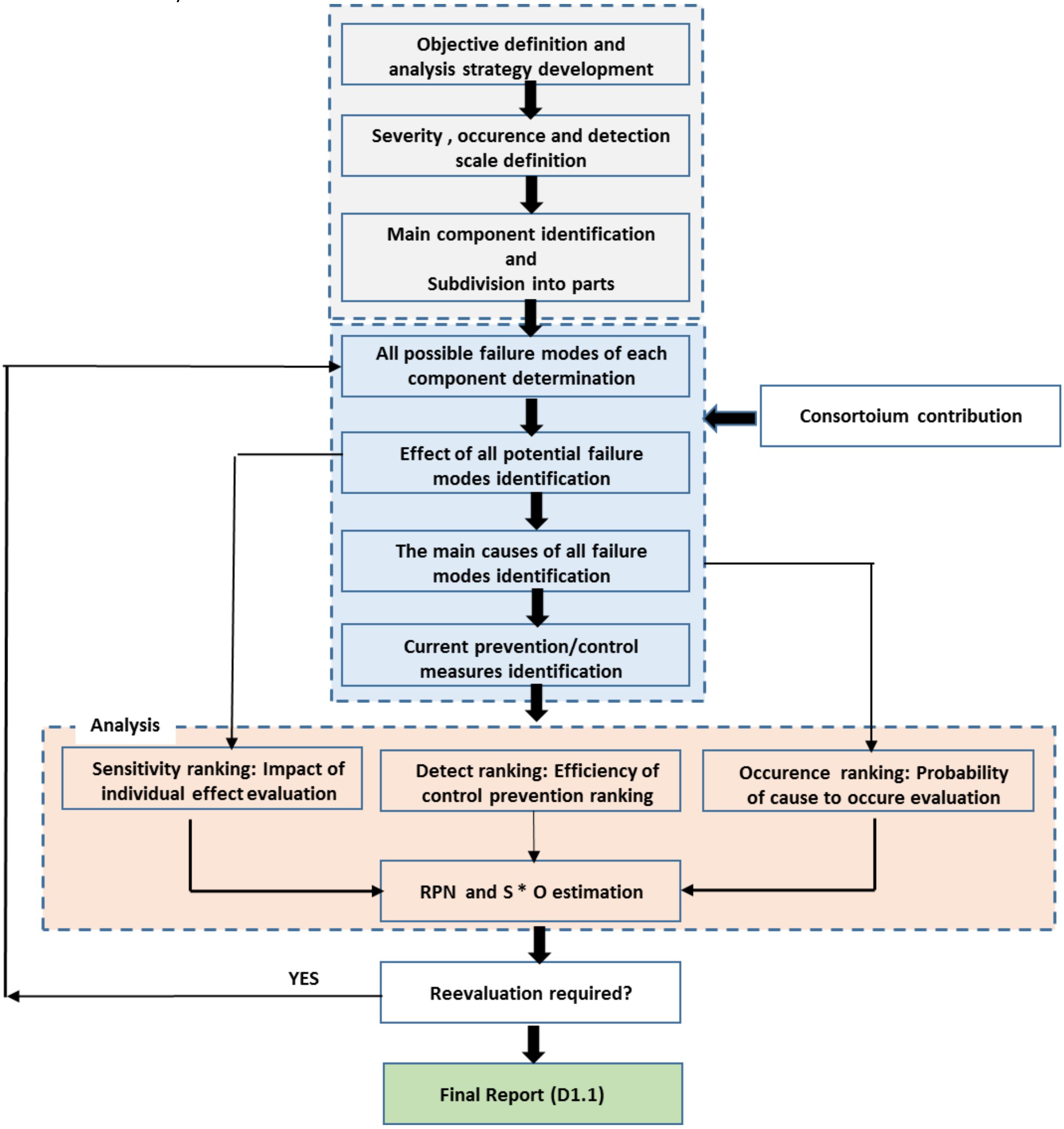

Figure 3: The main steps of the FMEA analysis for the Geo-Drill project

Severity, Occurrence and Detection scale definition

The method by which severity (S), frequency of occurrence (O) and detectability (D) are defined can vary depending on the field the FMEA is being used for. Each indicator is split into a specific number of categories and the number pertaining to the category is used to rate each failure listed in the FMEA depending on its nature. The definition of the categories can therefore be highly specific to the area for which the FMEA is being used. Direct input from experienced consortium members also shaped the categorization.

Severity, occurrence and detectability were each split into 10 categories, ranked from 1 to 10. The, detectability value was not considered as important as the severity and occurrence for this project. We assigned a lower scale to this, therefore also lowering the impact of this indicator on the analysis. The categories are shown in Tables 1-3. The severity rating ranges between 1 and 10, with systematic increase in rank. Each category is given a short definition and a more in-depth description to make the categorization clearer. Occurrence is often based on probability of failure or number of failures per produced item. For this project, it was categorized based on likelihood of failure within a certain timeframe. The rating range does not follow a traditional mathematical curve due to the nature of timing of failure in geothermal well drilling. This does not have an adverse effect on the results, as S and D are based on such formulas either. The highest rating for the occurrence is defined as the failure mode likely occurring more than once a day. The rating then decreases to “remote” which is defined as failure being likely to occur less frequently than once every seven years. For detection the scale ranges from the lowest value of 1 where failure is easily detected through reliable detection control before it becomes problematic, to 10 where failure cannot be detected before it affects the system notably.

Table 1: The severity ratings designed for the project

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

Table 2: The occurrence ratings designed for the project

	Ranking	Definition	Time Period	Per Item Failure Rates
Occurrence	10	Very High	More than once per day	>= 1 in 2
	9		Once every 3-4 days	1 in 3
	8	High	Once every week	1 in 8
	7		Once every month	1in 20
	6	Moderate	Once every 3 months	1 in 80
	5		Once every 6 months	1 in 400
	4		Once a year	1 in 800
	3	Low	Once every 1 - 3 years	1 in 1,500
	2	Very Low	Once every 3 - 6 years	1 in 3,000
	1	Remote	Once Every 7+ Years	1 in 6,000

Table 3: The detectability ratings designed for the project

	Ranking	Definition	Description
Detection	10	Almost Impossible	No known controls available to detect failure mode
	9	Very Remote	Very remote likelihood current controls will detect failure mode
	8	Remote	Remote likelihood current controls will detect failure mode
	7	Very Low	Very low likelihood current controls will detect failure mode
	6	Low	Low likelihood current controls will detect failure mode
	5	Moderate	Moderate likelihood current controls will detect failure mode
	4	Moderately High	Moderately high likelihood current controls will detect failure mode
	3	High	High likelihood current controls will detect failure mode
	2	Very High	Very high likelihood current controls will detect failure mode
	1	Almost Certain	Current controls almost certain to detect the failure mode. Reliable detection controls are known with similar processes.

Main component identification and subdivision into parts

We have performed an extensive literature review and consulted with experienced consortium members to identify the main components, and their main parts and or process step/input that comprise the complete Geo-Drill system. To make the process of filling out the FMEA more straightforward the base components of geothermal well drilling system were listed. The focus was on components experiencing fatigue, vibration, abrasion, corrosion and erosion due to formation fluid and lithology exposure. Failures of components (such as those in the drilling rig and electrical system) were therefore not included. Table 4 gives a short overview of all the components and their sub-components or process steps/inputs.

Table 4: The Geo-Drill system components and sub-components

Component	Sub-component or process step/input
Drill Bit	Bit Body/Matrix Failure Bit Shank Failures Failure of Striking/Anvil Face Insert Failure Insert Wear
Hammer Assembly	Anvil Chuck nut body failure Chuck nut threads Cylinder (internal sleeve) Hammer Back Head Hammer Body (External Casing) Piston Valve
Drill Pipe	Drill Pipe Drill pipe tool joint Drill pipe tool joint box Failure in friction weld between tool joint and drill pipe Tool joint

Drill Collar	Drill collars pin and box Tool joint failure
Drill Stabiliser	Stabiliser blades
Sensor	Accelerometer Generic Strain Gauge Thermal expansion Sensor connection through drill pipes Sensor line on drill pipes
Energy storage system	Energy storage system

Failure mode, effect and causes determination

The FMEA template document had a sheet for every component in the drill string, to allow the consortium members more leeway to complete the FMEA as it best suited them. To assist them in filling out the FMEA, the drill bit and hammer assembly sheets were provided with example entries (Appendix AA.1). In order to avoid making the template unnecessarily complicated, predetermined failure modes were not suggested to the partners, who were invited to complete the FMEA is an unbiased manner. They were also asked about failure prevention, including maintenance and other actions for reducing the occurrence or improving detection of failure modes.

Analysis of results

In order to maintain the confidentiality of partners' responses, a combined FMEA was collated. Taking average ratings is expected to skew the results towards lower values, potentially underestimating the importance of the most critical failure modes. The highest rankings selected by any of the partners were therefore used.

The failure mode containing the highest RPN value was chosen to be the main outcome. Additionally, if another failure mode had a higher value for either S or O, this particular failure mode was also included in the combined FMEA to avoid losing this information. This can result in a similar failure mode and effect having two different rankings for the same component. Based on different ranking systems, this information can be used to determine the criticality of each failure mode.

5 RESULTS AND DISCUSSION

5.1 Overview

The FMEA questionnaire focused on effects caused by fatigue, vibration, abrasion, corrosion and erosion in geothermal well drilling systems. Geothermal drilling in hard rock aggravates the operating conditions for materials used to fabricate downhole drilling tools. Their properties cannot meet the demands of these conditions, leading to drill string failure. The unfavourable geological conditions and the repeated impact for breaking the rock also cause severe bit bouncing and violent vibration. Tooth loss, tooth fracture, tooth wear and microcracks in addition to drill pipe fatigue from bending stress caused by buckling load are realistic examples of failure modes (an example is shown in Figure 1). Material types, grades and possible treatments (heat, nitriding, carburisation etc.) are identified, as most current failures, are due to poor quality materials, QA/QC and finishing processes. Some failures occur due to poor equipment selection and some are from improper usage. These failures cannot be controlled easily.

The tables in Sections 3.2 to 3.8 collate information contributed by the consortium partners, based on both the highest severity and the highest value for the RPN.

5.2 Drill bit

The most serious forms of potential damage for the drill bit (see figure 4) are shown in Table 5. Failure of the drill bits occur for a number of reasons:

- Wear of the drill teeth
- Fracture of the drill teeth
- Failure of the striking / anvil face
- Shank failures
- Drill body / matrix failures

This overview shows that the failure mode with the highest RPN value is insert wear that occurs when a compressive stress on the joint surfaces between the insert and the abrasive particle exceeds the breaking strength of the abrasive particle. Consequently, a stress concentration will be generated on these joint surfaces. The stress concentration increases fatigue damage on the tooth surfaces. The scouring effect, or the large quantity of hard cuttings flowing over the tooth surfaces, increases the abrasive on the insert surfaces. Also, when an insert surface encounters sharp edges or protrusions, the insert may suffer abrasion.

The next highest values of RPN are for failure of the striking/anvil face due to abrasion and erosion, followed by bit shank failure. These results show that by considering only at the RPN number, the most severe forms of damage and most frequent failure may be overlooked. The criticality (S*O) adds more weight to the severity and frequency of occurrence but these results do not distinguish among the nature of the failure modes (e.g. whether it is frequent yet mostly harmless or severe but infrequent). This analysis can affect how would be the best to proceed for protection and therefore, important to view all the values to take a final decision. The criticality score shows that the second most critical failure mode is insert failure because it is relatively severe and frequent. The succeeding failure modes based on this ranking are failure of striking/anvil face, bit shank failures and bit body/matrix failure. These values are therefore specifically considered, even though they are not frequent.

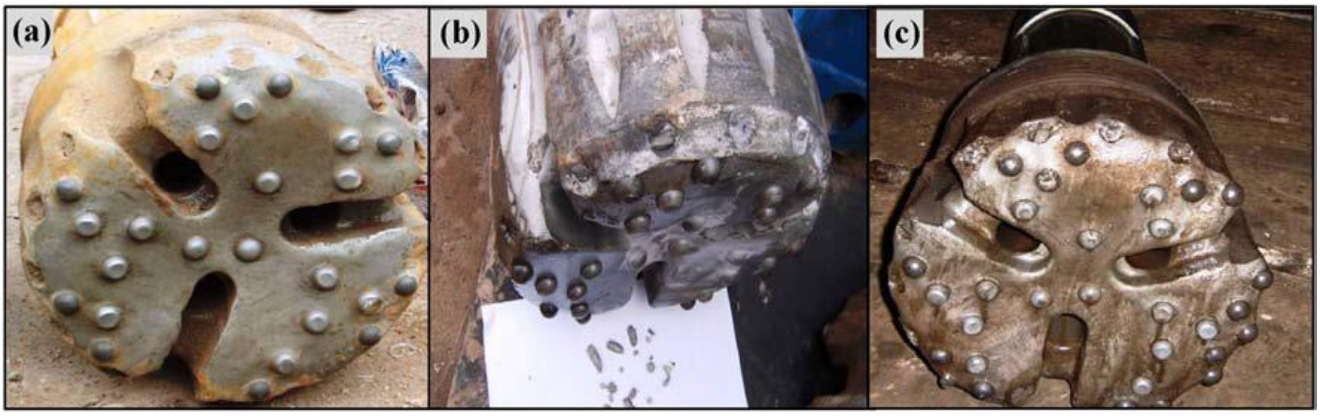

Figure 4: Failure modes of the drill bits: (a) bit shank failure, (b) insert failure, and (c) insert wear [‡]

[‡] M.T. Albdiry, M.F. Almensory, Failure analysis of drillstring in petroleum industry: A review, Department of Materials Engineering, College of Engineering, University of Al-Qadissiya, Al-Diwaniya, Iraq

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Table 5: The FMEA for drill bit based on the highest rated answers

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
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?			
Bit Body/Matrix Failure	Breakage of body.	Possibility of bit jamming if bit breaks into large piece(s). Loss of well, if body failure cannot be fished or milled out.	9	Poor quality materials. Erosion of body, by formation/flushing. Incorrect handling/operation	5	QC/QA of body materials. Care not to overrun bits (do not exceed anticipated design life). Handle correctly.	4	180	45
Bit Shank Failures	Shank of bit fails, leaving majority of bit in the well.	Fishing operation, sidetrack or loss of well.	9	Overheating of shank. Material defects. Poor manufacturing process.	5	Material inspections.	9	405	45
Failure of Striking/Anvil Face	Stress cracking, breakage of striking face.	Hammer becomes inoperable, possible major damage to hammer. Bit shank failure. Fishing operation or loss of hole.	9	Overheating of shank. Material defects. Poor manufacturing process.	5	None.	10	450	45
Insert Failure	Breakage	Premature failure, damage to bit matrix/body. Lower/loss of penetration. Increased tripping or inefficient drilling and number of usable teeth reduces	8	Poor quality inserts (sintering issues). Incorrect insertion of inserts into bit body/matrix. Fractured formations, improper usage/operation. Change in rock formation / local drilling conditions etc	7	Use of high quality inserts (high quality sintered carbides or PCD inserts) Operator training, attention to drill monitors.	5	280	56
Insert Wear	Premature wear	Loss of hole gauge, reduced ROP. Increased tripping time	9	Abrasive formations, improper operation. Poor quality Inserts	8	Correct selection of inserts. High strength sintered carbides required with good cohesive strength. Proper operation. Attention to drill monitors, to avoid excessive insert wear and possible wellbore problems	9	648	72

5.3 Hammer assembly

Table 6 shows the most serious forms of potential damage for the hammer assembly including:

- Anvil failures
- Chuck body nut failure
- Chuck nut thread failures
- Cylinder (internal sleeve)
- Hammer Back Head
- Hammer Body (External Casing)
- Piston
- Valve failures

This overview shows that the failure mode with the highest RPN value is hammer back head failure due to material fatigue. The failure of chuck nut body failure due to erosion is the second most important issue. Taking the score of criticality into consideration, one can see that the most critical failure mode is hammer body fracture, stress cracks and thread breakage. This is because this failure mode is relatively severe and frequent. The succeeding failure modes based on this ranking are hammer back head failure, chuck nut thread failure and chuck nut body failure. These modes are therefore specifically considered, even though they are not frequent.

Table 6: The FMEA for the hammer assembly based on the highest rated answers

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Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
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?			
Anvil	Overheating. Stress fractures. Excessive wear, due to contamination.	Loss of drilling time, through tripping out/in.	5	Poor quality material/manufacturing process(es). Contamination introduced to hammer (power/flushing medium).	5	QA/QC of materials. Visual inspection between runs. Operator training.	9	225	25
Chuck nut body failure	Excessive wear due to erosion of body material.	Loss of bit. Break-up of chuck, leading to drill string becoming stuck.	9	Poor materials. Improper flushing of cuttings. High velocity of cuttings in tight annulus. Turbulent flow around bit/chuck.	5	QA/QC of materials. Visual inspection between runs.	9	405	45
Chuck nut threads	Failure of threads at root of male section	Loss of bit. Fishing operation. Possible loss of well.	9	Incorrect torque setting of chuck into hammer body. Erosion of chuck body. Poor materials.	6	Torque monitors. Visual inspections, between runs. QA/QC	7	378	54
Cylinder (internal sleeve)	Overheating. Stress fractures. Excessive wear, due to contamination.	Loss of drilling time, through tripping out/in.	4	Poor quality material/manufacturing process(es). Contamination introduced to hammer (power/flushing medium).	5	QA/QC of materials. Visual inspection between runs. Operator training.	9	180	20
Hammer Back Head	Failure of male thread connection into hammer body and failure of male thread into drill string.	Loss of hammer. Loss of well.	10	Poor quality materials/manufacturing process(es). Incorrect handling, during make-up/break-out. Erosion from cuttings.	6	QA/QC of materials. Visual inspection between runs. Operator training.	8	480	60
Hammer Body (External Casing)	Fracture and stress cracks. Breakage of	Failure of hammer. Loss of well.	10	Poor quality materials/manufacturing process(es). Incorrect handling,	7	QA/QC of materials. Visual inspection between runs. Operator training.	5	350	70

	(female) threads.			during make-up/break-out. Erosion from cuttings.					
Piston	Overheating. Stress fractures. Excessive wear, due to contamination.	Loss of drilling time, through tripping out/in.	5	Poor quality material/manufacturing process(es). Contamination introduced to hammer (power/flushing medium).	5	QA/QC of materials. Visual inspection between runs. Operator training.	9	225	25
Valve	Stress Fracture	Loss of drilling time, through tripping out/in.	4	Poor quality material/manufacturing process(es). Contamination introduced to hammer (power/flushing medium).	4	QA/QC of materials. Visual inspection between runs. Operator training.	4	64	16

5.4 Drill pipe

The most serious forms of potential damage for the drill pipe (see figure 5) are listed in Table 7, which shows that the failure mode with the highest RPN value is thread galling at tool joint followed by the drill pipe fracture due to corrosion fatigue and fatigue. The criticality value shows that the most critical failure mode is drill pipe fracture due to corrosion fatigue and fatigue. This is because this failure mode is relatively severe and frequent. The succeeding failure modes based on this ranking are thread and tool face damage of tool joint.

Figure 5: Thread galling[§]

Figure 6: washout[**]

[††]

[§] https://trenchlesstechnology.com/drill-pipe-torque-devil-disguise/

[**] http://www.drillingformulas.com/washout-drill-pipe-experience/

Table 7: The FMEA for the drill pipe based on the highest rated answers

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
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?			
Drill Pipe	Fracture of pipe	Loss of drill string downhole	9	Corrosion fatigue, fatigue	6	Non-Destructive Testing (NDT) methods to detect crack formation	3	162	54
Drill pipe tool joint	Wall thickness reduction	External erosion of tool joints	6	Erosion and mechanical wear from formation material	6	Weld hardfacing material on tool joints	3	108	36
Drill Pipe tool joint box	Fracture of pipe due to cracking of tool joint	Loss of drill string downhole	9	Sulfide stress corrosion cracking (SSC) due to the drill pipe got stuck in the well for several days	4	Non-Destructive Testing (NDT) methods to detect crack formation	4	144	36
Failure in friction weld between tool joint and drill pipe	Weld fails	String needs to be fished out - Lost time	9	Wear and tear and cyclic bending stress causing fatigue failure	4	Drill pipe Inspection every 6000 meters, thickness measurements and visual inspection	2	72	36
Tool joint	Broken box or broken pin	String needs to be fished out - Lost time	9	Wear and tear and cyclic bending stress causing fatigue failure	2	Drill pipe Inspection every 6000 meters, thickness measurements and visual inspection	2	36	18
Tool Joint	Thread galling	Excessive torque at make-up (if rotary)	6	Improper design; rough operations of the crew; improper thread doping	5	Drilling rig operator awareness; quality procedure; make-up control, thread coating	8	240	30
Tool Joint	Thread galling	Loss of sealability	8	Improper design; rough operations of the crew; improper thread doping	4	Drilling rig operator awareness; quality procedure; make-up control, thread coating	8	256	32

Tool joint	Threads are damaged	String needs to be fished out - Lost time	9	Wear and tear and cyclic bending stress causing fatigue failure	6	Drill pipe Inspection every 6000 meters, thickness measurements and visual inspection	2	108	54
Tool joint	Tool face damaged leading to washout	String needs to be fished out - Lost time	9	Wear and tear and cyclic bending stress causing fatigue failure	6	Drill pipe Inspection every 6000 meters, thickness measurements and visual inspection	2	108	54

5.5 Drill collar

Table 8 gives a brief overview of the most serious forms of potential damage for the drill collar eg.

- Drill collars pin and box
- Tool joint failure (e.g. broken pins, damaged threads or tool face)

This overview shows that the failure mode with the highest RPN value is cracking leading to fracture at drill collar pin and box. Following this is tool joint failure due to broken box or pin, or due to thread damage.

Table 8: The FMEA for the drill collar based on the highest rated answers

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
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?			
Drill collars pin and box	Cracking leading to fracture	Drill string and components can be lost in hole, stuck	9	SSC, corrosion fatigue	5	NDT inspection, inspection of conditions of box; pits or cracks in threaded areas	4	180	45
Tool joint failure	Broken box or broken pin	String needs to be fished out - Lost time	10	Wear and tear and cyclic bending stress causing fatigue failure. String fatigue and whirling can also cause this (moreso for drill collar than drill pipes)	4	Inspection for fractures when beginning a well and before drilling the producing part of the well (thickness measurements and visual inspections)	3	120	40
Tool joint failure	Broken box or broken pin	String needs to be fished out - Lost time	10	Over or under torque in connection. Not enough thread compound used.	4	Care taken when connecting the drill collar.	4	160	40
Tool joint failure	Threads are damaged	String needs to be fished out - Lost time	10	Wear and tear and cyclic bending stress causing fatigue failure. String fatigue and whirling can also cause this (moreso for drill collar than drill pipes)	4	Inspection for fractures when beginning a well and before drilling the producing part of the well (thickness measurements and visual inspections)	3	120	40
Tool joint failure	Threads are damaged	String needs to be fished out - Lost time	10	Over or under torque in connection. Not enough thread compound used.	4	Care taken when connecting the drill collar.	4	160	40
Tool joint failure	Tool face damaged leading to washout	String needs to be fished out - Lost time	10	Wear and tear and cyclic bending stress causing fatigue failure. String fatigue and whirling can also cause this (moreso for drill collar than drill pipes)	4	Inspection for fractures when beginning a well and before drilling the producing part of the well (thickness measurements and visual inspections)	3	120	40
Tool joint failure	Tool face damaged leading to washout	String needs to be fished out - Lost time	10	Over or under torque in connection. Not enough thread compound used.	4	Care taken when connecting the drill collar.	4	160	40

5.6 Drill Stabiliser

The most serious forms of potential damage for the drill stabiliser (see Figure 7) are shown in Table 8. This overview shows that the failure mode with the highest RPN value is worn blade due to erosion – wear and tear from rocks.

Figure 7: worn down stabilizer blades‡‡

‡‡ Source:Internt

Table 8: The FMEA for the drill stabiliser based on the highest rated answers

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
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?			
Stabiliser blades	Blades are worn down due to erosion - wear and tear from rocks	Drilling direction and inclination may deviate. Drilling a new leg may be needed.	9	Erosion and mechanical wear and tear from rocks (more prominent when directional drilling)	9	Weld carbide on the Stabilisers blades to prevent wear and tear	5	405	81
Stabiliser blades	Blades are worn down leading to stress on tool joint leading to tool joint failure mechanisms (see e.g. Drill pipe)	String may need to be fished out, Lost time, Lost hole, Drill a new leg	9	Erosion and mechanical wear and tear from rocks (more prominent when directional drilling)	9	Weld carbide on the Stabilisers blades to prevent wear and tear	5	405	81

5.7 Sensor

The most serious forms of potential damage for the sensor are shown in Table 9. This reveals that the failure mode with the highest RPN value is erratic reading from strain gauge due to electromagnetic interference. Following this is insufficient resistance during assembly on the sensor connection through the drill pipes. Focusing on the criticality shows that the most critical failure mode is erratic reading from accelerometer due to damaged seismic mass or PZT layer. This is because this failure mode is relatively severe and frequent. The succeeding failure modes based on this ranking are erratic reading from strain gauge due to electromagnetic interference and sensor open or short circuit. These failure modes are therefore specifically considered, even though they are not frequent.

Table 9: The FMEA for the sensors based on the highest rated answers

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
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?			
Sensor (Accelerometer)	Erratic readings	Instrument readings are inaccurate or loss of power to energy storage systems	8	Damaged seismic mass or PZT layer	7	Data readings will be different compared with reference data and coexisting accelerometer banks	3	168	56
Sensor (Generic)	Open circuit	No data interaction between drill head and operator	6	High vibration may fracture conductive lines	7	If data line to sensors is lost, software will detect	1	42	42
Sensor (Generic)	Short circuit	Sensor will not function correctly	6	Damaged circuitry may cause exposed wires to contact	7	Spike detections within the software will detect these occurrences	3	126	42
Sensor (Generic)	Uncured inks	Instrument readings are inaccurate	5	Significant signal change caused through incorrect resistivity across the sensing element	6	Quality inspection of the correct/optimal resistivity measurements for the sensor during manufacturing process	2	60	30
Sensor (Strain Gauge)	Erratic readings	Instrument readings are inaccurate	6	Electromagnetic interference	7	Software will detect fluctuations	5	210	42
Sensor (Thermal expansion)	Inconsistent Readings	Instrument readings are inaccurate	6	The ambient temperature around the sensor cause expansion of the material or sensing elements	5	Data readings will be different compared with reference data and evaluation and statistical analysis will detect outlier results	4	120	30
Sensor connection through drill pipes	insufficient resistance during tool joint assembling	Impact on tool joint assembling causing excessive torque	6	Improper design, or improper manufacturing, or improper control; difficult make-up, errors in doping the thread causing excessive wear	5	Drilling rig operator awareness; quality procedure; make-up control	6	180	30
Sensor line on drill pipes	damage due to difficult drill pipe handling	Possible damage of the sensor line or difficult make-up of the tool joint due to difficult gripping of drill pipe	6	Difficult conditions during assembling, e.g. bad weather or night shift	5	Drilling rig operator awareness; quality procedure; make-up control	5	150	30

5.8 Energy storage system

The most serious forms of potential damage for the energy storage system are shown in Table 10. This overview shows that the failure mode with the highest RPN value is corrosion followed by short circuit. Focusing on the criticality shows that the most critical failure mode is short circuit and open circuit. This is because these modes are relatively severe and frequent. The succeeding failure modes based on this ranking are insufficient output voltage from battery, and deformation due to harsh environmental conditions. These modes are therefore specifically considered, even though they are not frequent.

Table 10: The FMEA for the energy storage system based on the highest rated answers

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
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?			
Energy Storage System	Battery has insufficient voltage output	Intermittent of power to sensors	5	Under or over charging due to infrequent drilling conditions.	8	Continuous monitoring will detect power losses to sensors	3	120	40
Energy Storage System	Corrosion	Unable to store energy or power sensors in drill head/string	7	Moisture present in current collecting contacts during manufacture or assembly processes.	4	Controlled environment during manufacturing and assembly to prevent moisture incursion	8	224	28
Energy Storage System	Deformation due to harsh environmental conditions	Effective storage of the voltage is limited	6	The structure holding the seismic mass may deform non uniformally resulting in reduced potential movement.	5	continuous monitoring of the ambient air temperature through thermocouples.	3	90	30
Energy Storage System	Open circuit	Loss of power to sensors	6	High vibration can cause loss of contact and fractures in conductive layers.	7	Monitoring system will detect power loss in sensors	1	42	42
Energy Storage System	Short circuit	Sensors and energy storage system will not function correctly	6	Damaged circuitry may cause exposed wires to contact.	7	Spike detections within the software will detect these occurrences	3	126	42

5.9 Summary and discussion

The previous sections show the ratings of the FMEA for the different systems and components. Table 11 collates this information and gives an overview of the highest values for each main scale within each system. This prevents components of a less-demanding system from being lost; these can still be important especially if we focus on specific systems, rather than the whole. The failure mode and effect with the highest value for each item is chosen for each case and their values are shown at the right in the table. For example, drill bit insert wear had the highest RPN number (648). This failure mode was therefore included in the Table 11.

Additionally, the RPN number 648 is also the highest RPN for any of the components in the drill string. This value is therefore highlighted. Within the hammer assembly, hammer back head and hammer body (external casing) have the highest severity. Within the drill collar, tool joint has the highest severity. These components are therefore listed under severity and the severity value is highlighted. Finally, drill stabiliser blade wear has the highest occurrence rating and is therefore listed. The occurrence rate is highlighted since it is the highest value.

Table 11: The highest rated components within each system based on RPN, S and O.

Component	Part	Failure Mode	Effect	RPN	S	O	S*O
Drill bit	Bit Body/Matrix	Breakage of body.	Possibility of bit jamming if bit breaks into large piece(s). Loss of well, if body failure cannot be fished or milled out.	180	9	5	*45*
	Bit Shank	Shank of bit fails, leaving majority of bit in the well.	Fishing operation, sidetrack or loss of well.	405	9	5	*45*
	Striking/Anvil Face	Stress cracking, breakage of striking face.	Hammer becomes inoperable, possible major damage to hammer. Bit shank failure. Fishing operation or loss of hole.	450	9	5	*45*
	Insert	Premature wear	Loss of hole gauge, reduced ROP. Increased tripping time	**648**	9	8	*72*
Hammer Assembly	Anvil	Overheating. Stress fractures. Excessive wear, due to contamination.	Loss of drilling time, through tripping out/in.	225	5	5	*25*
	Chuck nut body	Excessive wear due to erosion of body material.	Loss of bit. Break-up of chuck, leading to drill string becoming stuck.	405	9	5	*45*
	Chuck nut threads	Failure of threads at root of male section	Loss of bit. Fishing operation. Possible loss of well.	378	9	6	*54*
	Cylinder (internal sleeve)	Overheating. Stress fractures. Excessive wear, due to contamination.	Loss of drilling time, through tripping out/in.	180	4	5	*20*
	Hammer Back Head	Failure of male thread connection into hammer body and failure of male thread into drill string.	Loss of hammer. Loss of well.	480	**10**	6	*60*
	Hammer Body (External Casing)	Fracture and stress cracks. Breakage of (female) threads.	Failure of hammer. Loss of well.	350	**10**	7	*70*
	Piston	Overheating. Stress fractures. Excessive wear, due to contamination.	Loss of drilling time, through tripping out/in.	225	5	5	*25*
	Valve	Stress Fracture	Loss of drilling time, through tripping out/in.	64	4	4	*16*
Drill Pipe	Drill Pipe	Fracture of pipe	Loss of drill string downhole	162	9	6	*54*
	Drill pipe tool joint	Wall thickness reduction	External erosion of tool joints	108	6	6	*36*
	Drill Pipe tool joint box	Fracture of pipe due to cracking of tool joint	Loss of drill string downhole	144	9	4	*36*

	Failure in friction weld between tool joint and drill pipe	Weld fails	String needs to be fished out - Lost time	72	9	4	*36*
	Tool Joint	Thread galling	Loss of sealability	256	8	4	*32*
		Broken box or broken pin	String needs to be fished out - Lost time	36	9	2	*18*
		Threads are damaged	String needs to be fished out - Lost time	108	9	6	*54*
		Tool face damaged leading to washout	String needs to be fished out - Lost time	108	9	6	*54*
Drill Collar	Drill collars pin and box	Cracking leading to fracture	Drill string and components can be lost in hole, stuck	180	9	5	*45*
	Tool joint	Broken box or broken pin	String needs to be fished out - Lost time	160	**10**	4	*40*
		Threads are damaged	String needs to be fished out - Lost time	160	**10**	4	*40*
		Tool face damaged leading to washout	String needs to be fished out - Lost time	160	**10**	4	*40*
Drill Stabilizer	Stabilizer blades	Blades are worn down due to erosion - wear and tear from rocks	Drilling direction and inclination may deviate. Drilling a new leg may be needed.	405	9	**9**	***81***
		Blades are worn down leading to stress on tool joint leading to tool joint failure mechanisms	String may need to be fished out, Lost time, Lost hole, Drill a new leg	405	9	**9**	***81***
Sensor	Sensor (Accelerometer)	Erratic readings	Instrument readings are inaccurate or loss of power to energy storage systems	168	8	7	*56*
	Sensor (Generic)	Short circuit	Sensor will not function correctly	126	6	7	*42*
		Open circuit	No data interaction between drill head and operator	42	6	7	*42*
	Sensor (Strain Gauge)	Erratic readings	Instrument readings are inaccurate	210	6	7	*42*
	Sensor connection through drill pipes	Insufficient resistance during tool joint assembling	Impact on tool joint assembling causing excessive torque	180	6	5	*30*
	Sensor line on drill pipes	Damage due to difficult drill pipe handling	Possible damage of the sensor line or difficult make-up of the tool joint due to difficult gripping of drill pipe	150	6	5	*30*
Energy Storage System	Energy Storage System	Corrosion	Unable to store energy or power sensors in drill head/string	224	7	4	*28*
		Corrosion	Unable to store energy or power sensors in drill head/string	224	7	4	*28*
		Battery has insufficient voltage output	Intermittent of power to sensors	120	5	8	*40*

This table along with those shown in the previous Sections can be used to analyse the system as a whole. According to the RPN number, the most critical failure mode throughout the system is drill bit insert wear due to erosion from abrasive formations, which results in loss of hole gauge, reduced rate of penetration (ROP) and increased tripping time. After insert wear, hammer back head failure gets the highest RPN due to erosion from cuttings that results in loss of hammer and potential loss of well.

In terms of severity, erosion and impact, damage to the hammer back head and hammer body (external casing) pose the most serious threat because failure could result in significant loss of the well, forcing abandonment of the well. Tool joint failure due to wear and tear, cyclic bending stress, over or under torque in connection and not enough thread compound used also have the highest severity, though the potential risk is slightly less. This failure results in lost time in fishing out the drill string. After that, different failure modes of drill bit, hammer assembly, drill pipe, drill collar, drill stabiliser have the next highest severity. The impact of these modes can be as high as losing the well.

Worn drill stabiliser blade due to wear and tear or due to stress is the most frequent failure mode. Drill bit and hammer failure modes are less frequent, but effect the efficiency of drilling and may even result in loss of the well.

Different combinations of S, O and D can produce an identical RPN number. In addition, it may not be correct to assign equal weight to the three ratings that produce the RPN. For example, a partner might consider modes with high severity and/or high occurrence ratings to represent a higher risk than issues with high detection ratings. Hence, relying solely on the RPN might not be appropriate.

The Severity vs Occurrence plot provides an additional or alternative means to use the rating scales to prioritise the potential failure modes of the Geo-Drill System. In Figure 4, the points represent potential causes of failure and they are marked at the point where the Severity and Occurrence ratings intersect. To classify the high, medium and low risk, two lines: high priority line and low priority lines are shown. The lines may differ from problem to problem. It can be seen that most of the items are high priority except valve and piston of the Hammer assembly.

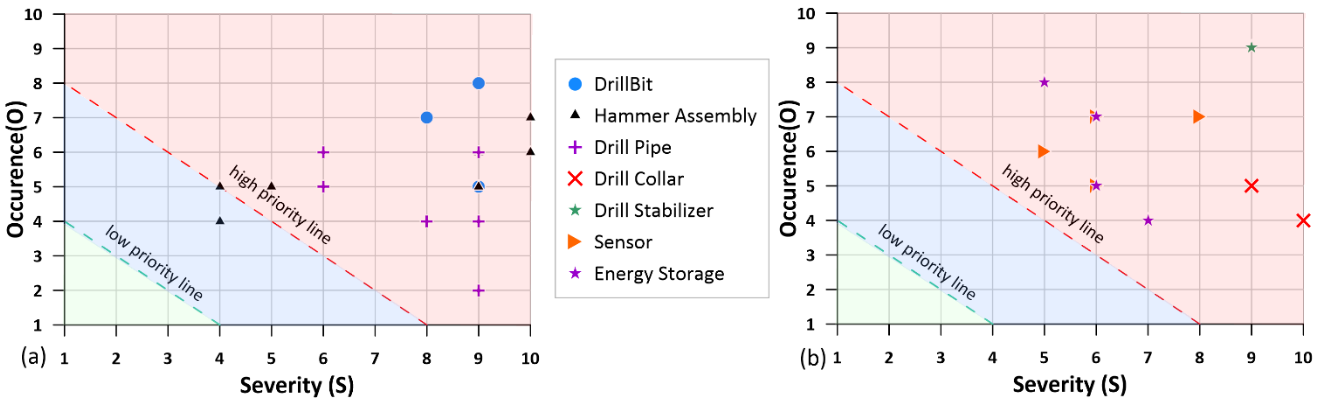

Figure 8: Severity vs Occurrence curve for all the items considered in this study. (a) Drill pipe, drill bit, hammer assembly; (b) Sensor, energy storage, drill collar, drill Stabiliser.

The FMEA carried out by the consortium provides a good overview of the different failure modes that can be experienced in geothermal well drilling. The analysis therefore give a strong basis on which a form of protection could be determined from requirements (such as the most severe forms of failure, the most frequent, the hardest to detect or a combination of these criteria).

6 CONCLUSIONS

The collated information showed that the failure modes influenced components in all the plants, although the degree of effects varied with different lithology and fluid properties. The main conclusions / findings from the FMEA are:

- All the failure modes being focused on are linked to severe cases in the system.
- The most critical case occurs in the drill bit insert wear due to erosion.
- Second most critical case occurs in the hammer (hammer back head failure) due to erosion.
- In terms of severity, erosion and impact, damage to the hammer back head and hammer body (external casing) pose the most serious threat. Tool joint failure due to wear and tear, cyclic bending stress, over or under torque in connection and not enough thread compound used also have the highest severity.
- Different failure modes of drill bit, hammer assembly, drill pipe, drill collar, drill stabiliser have the second highest severity.
- Worn drill stabiliser blade due to wear and tear or due to stress is the most frequent failure mode.
- Other drill bit and hammer failure modes are less frequent but effect the efficiency of drilling and may even result in loss of the well.
- There are numerous components which could potentially benefit from the use of more erosion resistant material including the drill bit, hammer, drill pipe, drill collar, drill stabiliser etc.

The results from the FMEA support the fact that fatigue, vibration, abrasion, erosion and corrosion resistant solutions are needed for the drill string in geothermal well drilling tools. It also provides an excellent basis to estimate the effect such solutions would have on the system.

Even if the solution could not protect the system from failure modes with the highest risk priority number, that does not mean that issues with lower RPNs or severity ratings could not lead to substantial gain as the financial consequence of each failure mode was not considered. The FMEA results will be used as guidelines for the continuation of the project to provide focus for the Geo-Drill solutions and to justify the requirement for protective solutions.

7 REFERENCES

[1] R. E. McDermott, R. J. Mikulak and M. R. Beauregard, The basis of FMEA, 2nd ed., New York: CRC Press, 2008..

[2] FMEA-FMEA, “FMEA RPN,” [Online]. Available: http://www.fmea-fmeca.com/fmea-rpn.html.

A. APPENDIX

AA.1. The FMEA

AA.1.1. The FMEA template

The sheets within the FMEA which was sent to the operators and consultants.

Sheet: Drill Bit

Geo-Drill Consortium Project ID:815319 - FMEA

Process/Product Name: Drill Bit (Current Commercial Offering)

Prepared By:

Responsible: Consortium Team

FMEA Date (Orig.):

(Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	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?				
Insert Failure	*Breakage*	*Premature failure, damage to bit matrix/body. Lower/loss of penetration.*	*8*	*Poor quality inserts. Incorrect insertion of inserts into bit body/matrix. Fractured formations, improper usage/operation.*	*7*	*Use of high quality inserts. Operator training, attention to drill monitors.*	*5*	*280*	*Better understanding of insert geometry, materials and coatings to reduce heat build up. Opertor training and drill rig monitoring systems.*	*Design and research team. Material suppliers, procurement.*		*0*	*0*	*0*	*0*

Drill Bits | Hammer Assembly | Drill Pipe | Drill Collar | Drill Stabilizer | ...

Document: D1,1

Version: **V1.0**

Date: 22 July 2020

Sheet: Hammer Assembly

Geo-Drill Consortium Project ID:815319 - FMEA

Process/Product Name: Hammer Assembly (Current Commercial Offerings)

Responsible: Consortium Team

Prepared By:

FMEA Date (Orig.):

(Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	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?				
Chuck nut body failure	*Excessive wear due to erosion of body material.*	*Loss of bit. Break-up of chuck, leading to drill string becoming stuck.*	*9*	*Poor materials. Improper flushing of cuttings. High velocity of cuttings in tight annulus. Turbulent flow around bit/chuck.*	*5*	*QA/QC of materials. Visual inspection between runs.*	*9*	*405*	*Surface coatings. Stress crack failure sensors. CFD programming to predict and optimise flow of cuttings, past chuck.*	*Design and research team. Material suppliers, procurement.*					
		Loss of bit							*Torque sensors*						

Drill Bits | **Hammer Assembly** | Drill Pipe | Drill Collar | Drill Stabilizer | ...

Document: D1,1

Version: **V1.0**

Date: 22 July 2020

Sheet: Drill Pipe

Geo-Drill Consortium Project ID:815319 - FMEA

Process/Product Name: Drill Pipe (Current Commercial Offerings)

Responsible: Consortium Team

Prepared By:

FMEA Date (Orig.): (Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O	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 Bits | Hammer Assembly | **Drill Pipe** | Drill Collar | Drill Stabilizer | ...

Document: D1,1

Version: **V1.0**

Date: 22 July 2020

Sheet: Drill Collar

Geo-Drill Consortium Project ID:815319 - FMEA

Process/Product Name: Drill Collar (Current Commercial Offerings) Prepared By:

Responsible: Consortium Team FMEA Date (Orig.): (Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	O'S	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 Bits | Hammer Assembly | Drill Pipe | **Drill Collar** | Drill Stabilizer | ...

Document: D1,1

Version: **V1.0**

Date: 22 July 2020

Sheet: Drill Stabiliser

Geo-Drill Consortium Project ID:815319 - FMEA

Process/Product Name: Drill Stabilizer (Current Commercial Offerings)

Prepared By:

Responsible: Consortium Team

FMEA Date (Orig.):

(Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	O.S	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 Bits | Hammer Assembly | Drill Pipe | Drill Collar | **Drill Stabilizer** | ...

Document: D1,1

Version: **V1.0**

Date: 22 July 2020

Sheet: Sensor

Geo-Drill Consortium Project ID:815319 - FMEA

Process/Product Name: Sensor Generic FMEA   Prepared By:

Responsible: Consortium Team   FMEA Date (Orig.): 25/06/2019   (Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	O,S	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 | Drill Collar | Drill Stabilizer | **Sensor** | Energy Storage System | ...

Document: D1,1

Version: **V1.0**

Date: 22 July 2020

Sheet: Energy Storage System

Geo-Drill Consortium Project ID:815319 - FMEA

Process/Product Name: Energy Storage Generic FMEA

Responsible: Consortium Team

Prepared By:

FMEA Date (Orig.): 25/06/2019 (Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O	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 | Drill Collar | Drill Stabilizer | Sensor | **Energy Storage System** | ...

Sheet: Severity Scale, Occurrence Scale and Detection Scale

Contains the ratings shown in Table 1,2,3 of the report

Document: D1,1

Version: **V1.0**

Date: 22 July 2020