RCM Program for a Well Intervention Tool – Below Packer Safety Joint

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Preface

As a culmination of our undergraduate studies in industrial engineering, we are pleased to present this bachelor thesis. This bachelor's thesis was an undertaking at Western University of Applied Sciences' Department of Mechanical and Marine Engineering (WNUAS).

In this thesis we got to delve into the subject of operations and maintenance engineering. Examining the topic from various perspectives and using a variety of research methods, and developing our skills in research, analysis, and critical thinking.

The thesis was provided to us, and has been in collaboration with Entech Solutions AS. We would like to give a special thanks to Jan Tore Tveranger and Anthony Kent from Entech for their support, expertise, and feedback. They have been instrumental throughout this process and have helped shape and refine our ideas. We would also like to thank Schlumberger for their assistance and input during the process.

Lastly, we would like to express our gratitude to our thesis advisor, Prof. Maneesh Singh for their invaluable knowledge, support, and encouragement throughout the research process.

Abstract

The focus of the bachelor thesis is operations- and maintenance engineering, specifically on the Reliability Centered Maintenance (RCM) methodology and its potential to improve reliable and effective maintenance practices. Entech, operating in the competitive upstream oil and gas industry, aimed to extend the lifecycle of its product, Below Packer Safety Joint (BPSJ), by developing more comprehensive analyses and maintenance routines. Analysis of the product's functions and components was performed using the RCM methodology.

BPSJ is a product installed in a tubing-conveyed perforating string, which detonates explosives down at the bottom of the well to access oil. During this process, the string may become stuck, which can have severe economic consequences, including the loss of expensive equipment or even the entire wellbore. The BPSJ product is designed to provide a release point in the string, so that the most expensive equipment can be freed in the event of the string becoming stuck. Increasing the reliability of this tool is therefore essential to ensure it works as intended when needed.

The subsystem, interfaces, and failures were analyzed using RCM. The results from Critical Item Selection and FMECA were presented, with FMECA adapted to fit cybersecurity concepts. This change allowed for a more comprehensive assessment by analyzing potential vulnerabilities in the subsystem related not only to safety but also to security. Finally, specific maintenance activities were recommended for components that were more prone to failure.

It is concluded that RCM contributes to improving the system's reliability and reducing the risk of failure. By using the RCM methodology, maintenance measures were identified that will increase the lifecycle of BPSJ and make it more cost-effective. However, it should be noted that RCM is not infallible and may potentially overlook failures or other factors. The lack of accurate and reliable data can also limit the conclusions that can be drawn from an RCM analysis. Therefore, it is recommended to periodically review and update the RCM analysis to ensure its continued relevance and effectiveness.

Sammendrag

Fokuset i bacheloroppgaven er drift-og vedlikeholdsteknikk, spesielt på metodikken Reliability Centered Maintenance (RCM) og dens potensial for å forbedre pålitelige og effektive vedlikeholds-rutiner. Entech, som opererer i den konkurransepregete oppstrøms olje- og gassindustrien, ønsket å forlenge livssyklusen til sitt produkt, Below Packer Safety Joint (BPSJ), ved å utvikle grundigere analyser og vedlikeholdsrutiner. Analyse av produktets funksjoner og komponenter ble utført ved hjelp av RCM-metodikken.

BPSJ er et produkt som installeres i en "tubing-conveyed perforating string", som er en rørstreng som detonerer eksplosiver i en oljebrønn for å få tilgang til olje. I denne prosessen kan strengen sette seg fast, noe som kan ha alvorlige økonomiske konsekvenser, inkludert tap av dyrt utstyr eller til og med hele oljebrønnen. BPSJ produktet er utviklet for å kunne være et brytningspunkt i strengen, slik at man kan befri det dyreste utstyret i tilfelle strengen setter seg fast. Å øke påliteligheten til dette verktøyet er derfor essensielt for å sikre at det fungerer som det skal når det trengs.

Delsystemet, grensesnittene og funksjonsfeilene ble analysert ved bruk av RCM. Resultatene fra Critical Item Selection og FMECA ble presentert, med FMECA tilpasset begreper fra cybersikkerhetsområdet. Denne endringen muliggjorde en mer omfattende vurdering ved å analysere mulige sårbarheter i delsystemet ikke bare relatert til «safety», men også til «security». Til slutt ble spesifikke vedlikeholds-aktiviteter anbefalt for komponenter som var mer tilbøyelige til å feile.

Det konkluderes med at RCM bidrar til å forbedre systemets pålitelighet og redusere risikoen for feil. Ved å bruke RCM-metoden ble det identifisert vedlikeholdstiltak som vil øke livssyklusen til BPSJ og gjøre det mer kostnadseffektivt. Det gjøres imidlertid oppmerksom på at RCM ikke er feilfritt og kan potensielt overse funksjonsfeil eller andre faktorer. Mangelen på nøyaktig og pålitelig data kan også begrense konklusjonene som kan trekkes ved en RCM-analyse. Det anbefales dermed å periodisk gjennomgå og oppdatere RCM-analysen for å sikre dens fortsatte relevans og effektivitet

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Definitions

Likelihood:	chance of something happening [ISO 31000 [1]]
Risk:	combination of the probability, (or frequency) of occurrence of a defined hazard and the magnitude of the consequences of the occurrence [(BS 3811) (Z008) [2]]
Hazard:	situation that could occur during the lifetime of a product, system or plant that has the potential for human injury, damage to property, damage to the environment, or economic loss [(BS 3811) (Z008) [2]]
Failure:	the termination of the ability of an item to perform a required function [(Z008) [2]]
Criticality:	numerical index of the severity of a failure or a fault combined with the probability or frequency of its occurrence [BS EN 13306 [3]]
Item:	any part, component, device, subsystem, functional unit, equipment, or system that can be individually considered [(Z008) [2]]
Availability:	ability to be in a state to perform as required [ISO 14224 [4]]
Reliability:	ability of an item to perform a required function under given conditions for a given time interval [ISO 14224 [4]]
Maintenance:	is the combination of all technical and management actions intended to retain an item in, or restore it to, a state in which it can perform as required [ISO 14224 [4]]
Functional requirement:	is a specification of the performance criteria related to a function [5, p. 78]
Asset:	an item, thing or entity that has potential or actual value to an organization [ISO 55000 [6]]
Cost-effectiveness:	that the task does not cost more than the failure(s) it is going to prevent. [Z008 [2]]
Life cycle:	the stages through which a product, system, service, or project passes from conception through retirement [ISO 15288 [7]]
Item:	part, component, device, subsystem, functional unit, equipment, or system that can be individually described and considered [BS EN 13306 [3]]
Malicious:	the term “malicious” is used intentionally to clearly differentiate safety from security and thereby avoid an unnecessary overlap in the taxonomy of quality factors. [8]

Abbreviations

- BPSJ – Below Packer Safety Joint
- TCP – Tubing Conveyed Perforating String
- RCM – Reliability Centered Maintenance
- FFA – Functional Failure Analysis
- FMECA – Failure Mode, Effects and Criticality Analysis
- FSI – Functional Significant Item
- MCSI – Maintenance Cost Significant Item
- MSI – Maintenance Significant Item
- FAST – Function Analysis System Technique

1. Introduction

This chapter will start by introducing the company Entech AS, the context in which the tool BPSJ is being utilized, the motivation of the project, aim and objectives, followed by project limitations.

1.1 Background

1.1.1 Entech AS

The upstream oil and gas industry is highly competitive and constantly evolving, with new technologies and innovations driving progress and shaping the future of the sector. Entech, a platform for operators and entrepreneurs, aims to be at the forefront of this transformation by providing a space for innovative ideas to be developed and brought to market. The company has established offices in Norway as well as North- and South America.

Entech's vision is to become the preferred venture partner for hardware technology development and commercialization in the upstream oil and gas industry. To achieve this goal, the company has developed a mission to promote market-driven innovation and implement lean product development and commercialization practices. These efforts have resulted in an accelerated idea-to-market lifecycle and the successful delivery of three different product prototypes in the first three months of operation. [9]

1.1.2 Below Packer Safety Joint (BPSJ)

The subject of this thesis paper is the design of Entech's below packer safety joint (BPSJ), which serves as a safety mechanism in a tubing conveyed perforating string (TCP) used for oil well perforation. The BPSJ is installed in the TCP string to prevent the string from getting jammed, which can have significant financial consequences, such as the loss of expensive equipment or even the entire oil well. Therefore, the BPSJ assumes crucial significance as it provides a means of rescuing equipment in the event of such an occurrence. [10]

1.1.3 Motivation of the Project

The selection of the project was based on two primary factors. Firstly, the below packer safety joint (BPSJ) has exhibited mechanical and material failure after only being employed twice during a six-month period, and secondly, the tool's maintenance program is currently limited. Consequently, an operations and maintenance evaluation of the tool is necessary, analysing each component failure and identifying the causes, mechanisms, and effects of failure. This assessment will provide insights into the critical components that may cause substantial damage upon failure and assist in the development of an effective maintenance program for Entech based on these findings.

1.2 Project Aim and Objective

The aim of the thesis project is to develop a comprehensive maintenance program for a new well intervention tool – a Below Packer Safety Joint (BPSJ) for Entech Solutions AS.

The objectives of this thesis are:

- The objectives are longer equipment lifespan, decreased need for unnecessary maintenance, and fewer serious equipment failures.

- Tool that ensures sustained performance and longevity. The program will be tailored to the specific needs and expectations of Entech Solution AS and their customers.

- The failure of equipment will be analysed for safety and security considerations.

1.3 Scope of the Project

The thesis area of study will be as follows:

1. Review of Maintenance Theory and Tools: The scope of work includes a comprehensive review of maintenance theory and tools such as FFA, FMECA and Cause- and effect analysis to ensure that the maintenance program is based on best practices.
    a. Literary study on RCM, downhole safety packers and relevant industry standards.
    b. Collecting qualitative data (pictures, specifications, conditions, and experiences) from Entech and the customer that is currently using the tool.
2. Alignment with ISO 14224 Standard: The maintenance program will be developed with a focus on compliance with the ISO 14224 standard to ensure its effectiveness and efficiency.

3. Tailored to Client Needs: The program will be tailored to the specific needs and expectations of Entech Solution AS and their customers to ensure its relevance and usefulness.
    a. Conduct an AISI 4140 corrosion test in different solutions, and research recommended material coating.
    b. Produce recommended maintenance actions list for checking, testing, and inspecting the tool to extend the life cycle of the BPSJ.
4. Cost-Effectiveness: The program will be designed with a focus on cost-effectiveness to ensure that it is affordable and sustainable for Entech Solution AS and their customers.

1.4 Limitations

Limitations of the thesis maintenance planning on safety guard BSPJ are:

- The geographical distance of the tool poses a logistical challenge to the research team, which may cause delays.
- Due to the recent implementation of the BPSJ tool, the study relies on limited prior experience and not on comprehensive statistical analysis, which may limit accuracy and reliability.
- The report does not account for the possibility of human error leading to tool failure since the BPSJ tool is largely self-sufficient, requiring minimal direct operator intervention during operation, except for retrieval from the well and between campaigns.
- The tool's current inspection and maintenance plan is limited, thus using it as a starting point for creating a maintenance plan will not be sufficient.

2. Maintenance Theory

This chapter addresses the term maintenance, various maintenance categories, the RCM methodology, including the steps of Marvin Rausand's RCM analysis.

2.1 What is Maintenance?

According to the book "System Reliability Theory: Models, Statistical Methods, and Applications" by Arnljot Høyland and Marvin Rausand, maintenance is defined as "The combination of technical, administrative, and managerial actions, during the life cycle of an item, intended to retain it in, or restore it to, a state in which it can perform the required function." This definition emphasizes the primary objective of maintenance, which is to ensure that an asset functions as required throughout its operational life by preserving its original state or by restoring it to that state in case of deterioration. Additionally, the definition acknowledges the cross-disciplinary nature of maintenance, as it necessitates considering various aspects, such as technical, administrative, and managerial actions. [5, p. 361]

An alternate definition of maintenance is presented in the book “Maintenance and Reliability Best Practices”, which defines maintenance as "The act of keeping an asset in its original condition or restoring it to an acceptable condition. [11, p. 12] Furthermore, it included the objective of achieving a specified level of performance, availability, and/or useful life, at the lowest possible cost, consistent with safety, environmental, and other relevant factors. This definition shares the same primary objective as the previous definition, which is to ensure that an asset performs its intended function. However, it differs in that it specifies additional factors that must be considered, such as safety, environmental impact, and cost-effectiveness, in achieving a specified level of performance, availability, and/or useful life. By incorporating these factors, this definition highlights the importance of considering the broader context in which maintenance activities are performed. [11, p. 50]

Maintenance practices have evolved throughout history. During World War II, there was a growing need for equipment reliability. This shift in emphasis from maintenance after failure to maintenance before failure was driven by the need to ensure that equipment was operational when it was needed most. The consequences of equipment failure during wartime were too great to ignore, making it imperative to ensure that maintenance activities were carried out proactively. This change in approach laid the groundwork for the development of various categories of maintenance that will be discussed in this chapter. [12, p. 174]

2.1.1 Empirical Bathtub Curve

The bathtub curve is a widely used tool in the field of reliability engineering for analysing the behaviour of products and systems over their lifetime. It provides a graphical representation of the failure rate function z(t) of a product or system over time, taking its name from the distinctive shape of the curve, which resembles a bathtub. The curve of the bathtub creates three distinct periods. [5, p. 21]

Burn-in period: This phase is characterized by a high initial failure rate. Errors that occur in this phase are often caused by manufacturing or design errors.

Useful life period: This phase is characterized by a low and relatively constant percentage of errors. Failures that occur in this phase are often due to random or accidental events and are not related to the age of the product or system.

Wear-out period: This phase is characterized by a gradual increase in the failure rate over time. Failures that occur in this phase are often caused by wear, aging and degradation of the components or materials.

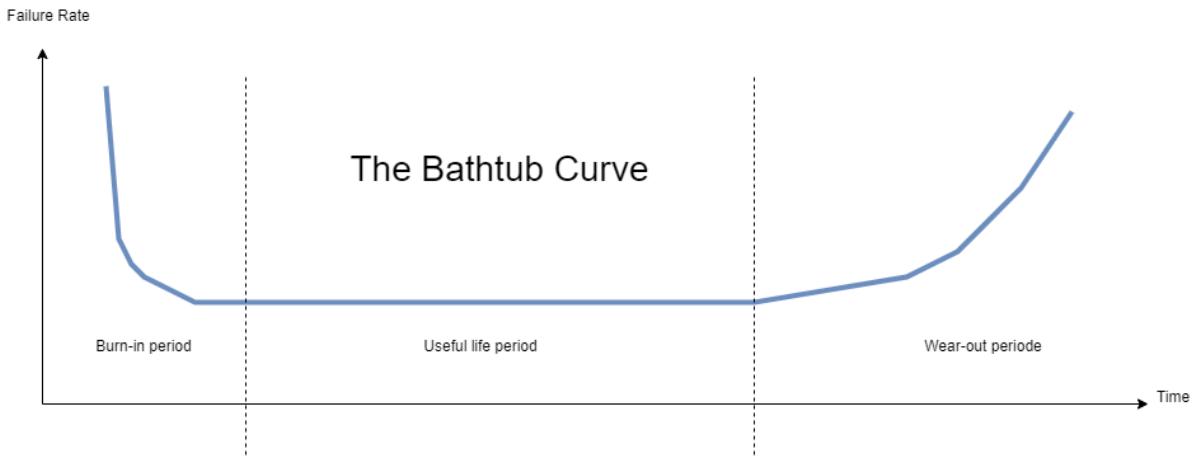


Figure 1 The Bathtub Curve [5, p. 21]

2.1.2 Maintenance Categories

The BS-EN-13306-2010 standard defines failure as "termination of the ability of an item to perform a required function." [3, p. 9] This definition is consistent with the notion of maintenance, which aims to ensure that assets perform their intended functions. In this context, failure is an event that prevents an asset from functioning as required. By understanding the nature of a failure, maintenance professionals can implement appropriate maintenance practices that are tailored to the needs of their assets.

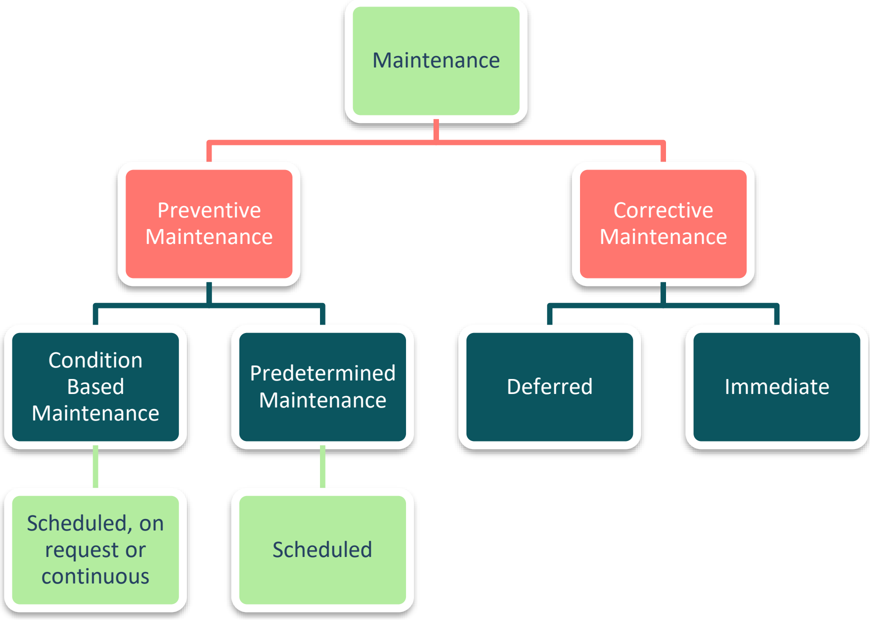


Figure 2 Maintenance categories BS-EN-13306 [3]

Maintenance activities can be broadly classified into three types: corrective, preventive, and predictive. In addition to this classification, maintenance can also be carried out in two ways: planned or unplanned. Unplanned maintenance typically involves corrective maintenance, which is not the optimal way to carry out maintenance due to the potential for unexpected downtime and increased costs. In contrast, planned maintenance provides an opportunity to choose the optimal and most cost-effective maintenance method based on the specific needs and circumstances of the asset. Several methods can be employed during planned maintenance, and in the following section the three methods will be discussed.

Corrective Maintenance (CM): CM is frequently referred to as repair and is done after an item fails. The goal is to swiftly restore the item to the state where it is functioning as intended. This is accomplished by either fixing or replacing the faulty component. Another name for CM is breakdown maintenance or run-to-failure maintenance. [5, p. 364]

Preventive Maintenance (PM): PM is when an item undergoes scheduled maintenance even though it is operating as intended. The objective is to prevent failures from occurring and to make it less probable that future failures may occur. Inspections, adjustments, part replacements, lubrication, and repairs to worn-out equipment are all examples of PM actions. Even when functionality remains intact, this type of maintenance is routinely carried out. The categories of PM include *age-based-*, *clock-based-*, *condition-based (predictive)-,* and *opportunity maintenance*. [5, p. 363]

Predictive Maintenance: Predictive or condition-based maintenance is an attempt at evaluating an assets condition. The objective is to find the most cost-effective maintenance activity, that can be scheduled and performed before the asset fails. It's a way of attempting to predict the future trajectory of the assets' condition. Different methods are used in determining when the maintenance activities should be scheduled. [11, pp. 55-56]

Conducting maintenance is an essential aspect of any system, equipment, or infrastructure to ensure that it operates reliably and efficiently. Maintenance is important for several reasons:

- it helps to prevent equipment failure and downtime. Regular maintenance can help identify potential problems before they become serious, and thus prevent unexpected breakdowns that could lead to costly repairs and lost productivity.

- maintenance can improve the lifespan and performance of the equipment. By ensuring that the equipment is well-maintained, it can perform at its optimal level and last longer, resulting in significant cost savings.

- maintenance can help to ensure the safety of the people who operate and use the equipment. Regular inspections and maintenance can identify potential hazards and risks and help to prevent accidents and injuries.

In sum, maintenance is a critical aspect that ensures the reliability, efficiency, and safety of any system or equipment. Maintaining equipment in good condition helps prevent costly repairs, downtime, and accidents. [11, pp. 50-59]

2.2 Reliability-Centered Maintenance (RCM)

Reliability-centered maintenance (RCM) was initially developed in the aircraft industry but has since been implemented across various industries. Empirical evidence from these industries has shown that the availability of systems can be sustained, and in some cases, enhanced while substantially decreasing the costs associated with preventive maintenance (PM). [5, p. 401]

The RCM methodology is used to identify the optimal method of maintenance or maintenance strategy for the equipment or system in use. The primary focus of the RCM methodology is on a systems functionality versus a systems hardware. The objective is to concentrate on the most essential functions of a system and reduce or eliminate unnecessary maintenance tasks. RCM was developed to achieve the most cost-effective PM program by balancing the costs and benefits. [5, p. 401]

The methodology offers a structured framework to determine the maintenance requirements of a system or piece of equipment, so that it continues to perform its required function. It is based on the idea that maintenance should be focused on the components of a system that are most likely to fail. The process involves identifying the critical components of a system, analyzing their failure modes, and then developing maintenance strategies to reduce the likelihood of failure. While not all failures can be avoided by PM, it is important to understand the potential effects of each failure as well as its likelihood. A PM task must reduce the predicted loss due to material damage, production loss, environmental damage, and/or employee injuries in order to be effective. [5, pp. 363, 402]

The book "System Reliability Theory: Models, Statistical Methods, and Applications" by Arnljot Høyland and Marvin Rausand gives an overview of the multiple benefits of completing an RCM analysis. Some of which include:

1. Increased system availability: RCM can identify potential failure modes and develop appropriate maintenance strategies to reduce the likelihood of system downtime.

2. Cost savings: By optimizing maintenance activities, RCM can help to reduce maintenance costs and increase the efficiency of maintenance operations.

3. Improved safety: RCM can help to identify and address potential safety hazards, reducing the risk of accidents and injuries.

4. Improved decision-making: RCM provides a systematic approach to decision-making about maintenance activities, ensuring that decisions are based on objective criteria and data.

5. Better understanding of system performance: RCM can help to identify the critical components and failure modes of a system, providing a better understanding of system performance and potential failure modes.

For an equipment to be deemed to have undergone an RCM analysis, it should provide answers to the following questions: [5, p. 402]

1. What is the purpose- and function of the equipment? (Functions)
2. In what ways may the equipment fail to fulfill its intended function? (Functional failures)
3. What is the failure caused by? (Failure modes)
4. When each failure occurs, what happens? (Failure effects)
5. What significance does each failure have? (Failure consequence)
6. What steps can be taken to anticipate or prevent each failure? (Initiative-taking tasks and task intervals)
7. What action should be taken if the appropriate PM task is unavailable? (Standard practices or default actions)

In conclusion, RCM provides a structured framework to identify and prioritize maintenance tasks for systems and equipment. By focusing on the most essential functions of a system and reducing unnecessary maintenance tasks, RCM can help to increase system availability, reduce maintenance costs, improve safety, and enhance decision-making. By asking the right questions and analyzing failure modes, organizations can develop effective maintenance strategies that balance the costs and benefits of preventive maintenance. Implementing RCM can be a valuable investment for organizations looking to improve the reliability and performance of their systems and equipment.

3. Method

This chapter describes the method used to carry out the work with the BPSJ. Methods used are Reliability Centered Maintenance, Cause-and-Effect analysis, and an analysis of the cybersecurity domain for insights to incorporate into the FMECA process.

3.1 Qualitative and Quantitative Method

Data collecting methods are divided into two categories, qualitative and quantitative. Qualitative model is a judgement-based approach where a numerical value is not calculated, instead ranking given by low, medium, and high is used. This makes the results subjective, and they are based on opinion and experience. The advantage of qualitative method is that it is quick and inexpensive, and the results are easy to present. [13]

Quantitative model is a model-based approach, where the numerical value is calculated. The advantages of using this model compared to qualitative model is that this approach is methodical, consistent, and well-documented, and can be easily updated based on inspection findings. [13] This rapport will be based solely on a qualitative method due to a lack of reliability data.

3.2 The steps of RCM

There are a series of twelve steps that are suggested by M. Rausand (2004) when completing an RCM analysis, but this thesis will consider the steps one through seven which are the steps relevant to the analysis of the BPSJ. [5, p. 403]

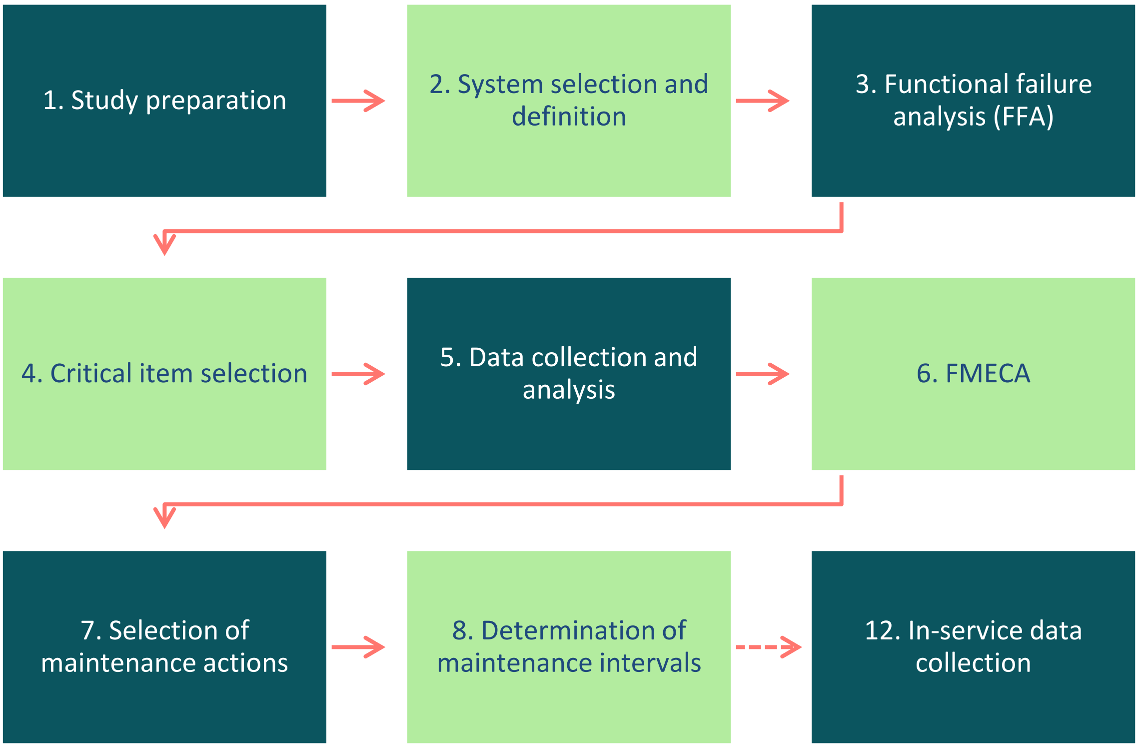


Figure 3 RCM Steps

Step 1: Study Preparation

The RCM analysis starts with study preparation where the scope of the analysis is defined. During this initial step, applicable laws, regulations, environmental expectations, and standards are taken into consideration and assessed. It is also imperative to create or acquire technical drawings and process and instrumentation diagrams (P&ID), as well as document any modifications made to the system at a later stage. [5, p. 403]

Step 2: System Selection and Definition

In the second step, it is determined which level of hierarchy is to be included in the RCM analysis. Resources are limited, so even if the whole plant had been used by the analysis, it is more cost-effective to prioritize some components over others. There are two questions that are considered before the decision to possibly perform an RCM analysis is made: [5, p. 403]

1. To which systems are an RCM analysis beneficial compared with more traditional maintenance planning?
2. At what level of assembly (plant, system, subsystem) should the analysis be conducted?

A technical hierarchy for the plant needs to be developed. In Marvin Rausand's book, the hierarchy is divided into four levels. This is the tag number system often used in the oil and gas industry. This is just one way of forming a hierarchy, for other types of plant that need to be edited to be optimal. [5, p. 403]

Maintainable item: is an item that can perform a significant function separated from the rest.

Sub-System: is a smaller part of a larger system, which can function alone.

System: is a set of subsystems that perform a main function in the plant.

Plant: is a set of systems that function together to provide some sort of output.

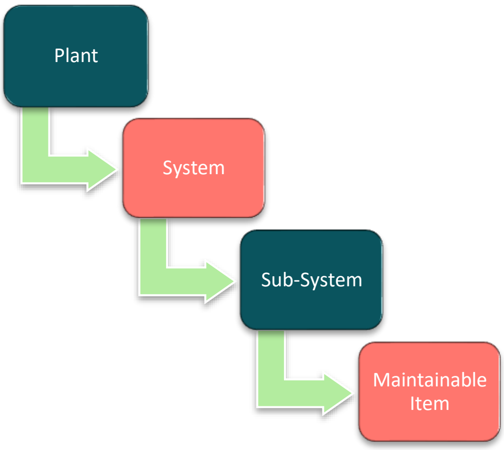


Figure 4 Technical Hierarchy

Step 3: Functional Failure Analysis (FFA)

Once the system selection and definition has been performed, one can begin functional failure analysis. The FFA facilitates the development of maintenance plans that aim to improve the reliability and availability of the system. [5, p. 405]

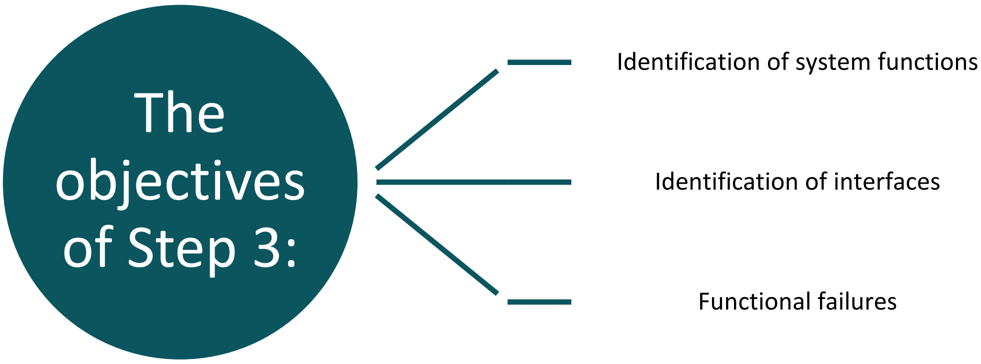


Figure 5 Step 3 - Objectives

Identification of system functions: First, the item's main function must be identified and the performance criteria. A function analysis system technique (FAST) diagram is a tool that can be used to analyze a system and its potential failures. It helps us to understand how the system works and how different components interact with each other. A FAST diagram is a useful tool for breaking down complex systems into smaller, more manageable components, and understanding how they work together to achieve the desired function. The functions that are identified define the scope of the analysis. [14, pp. 145-149]

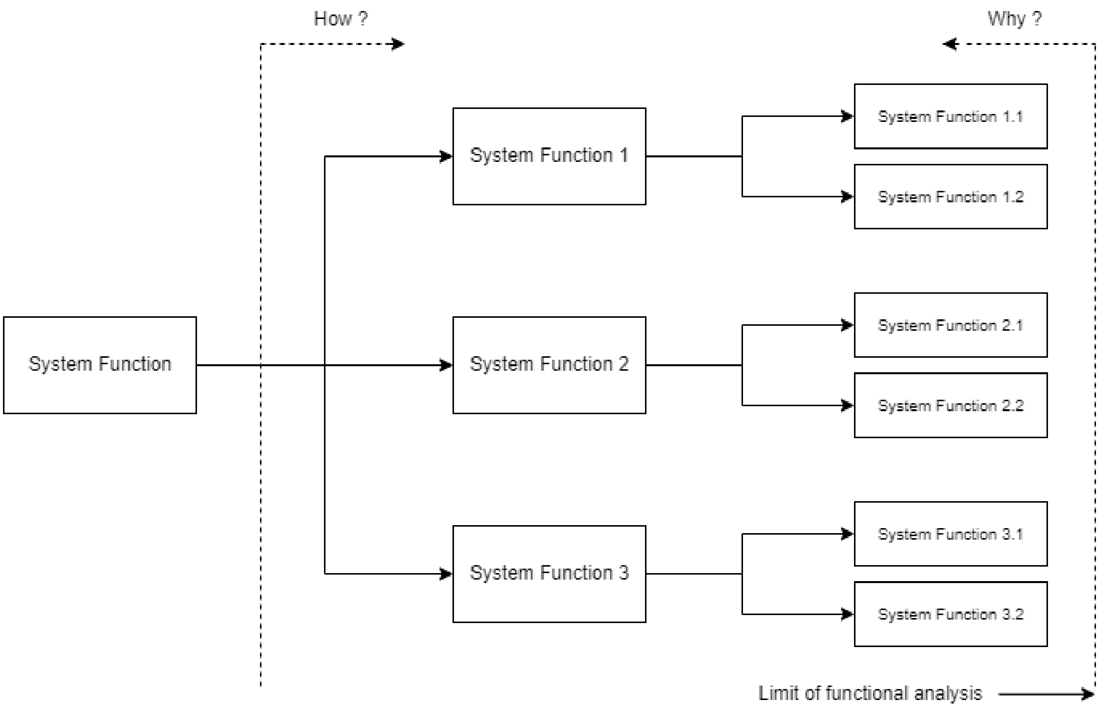


Figure 6 Example of a FAST diagram [5, p. 81]

Identification of interfaces: The reliability of a technical system depends on its interfaces with the outside world, so it is necessary to study how these interfaces influence the system. Interfaces is system, system boundary, outputs, inputs, boundary conditions, support and external threats. The identification process will be done through a block diagram as shown below. [5, pp. 75-76]

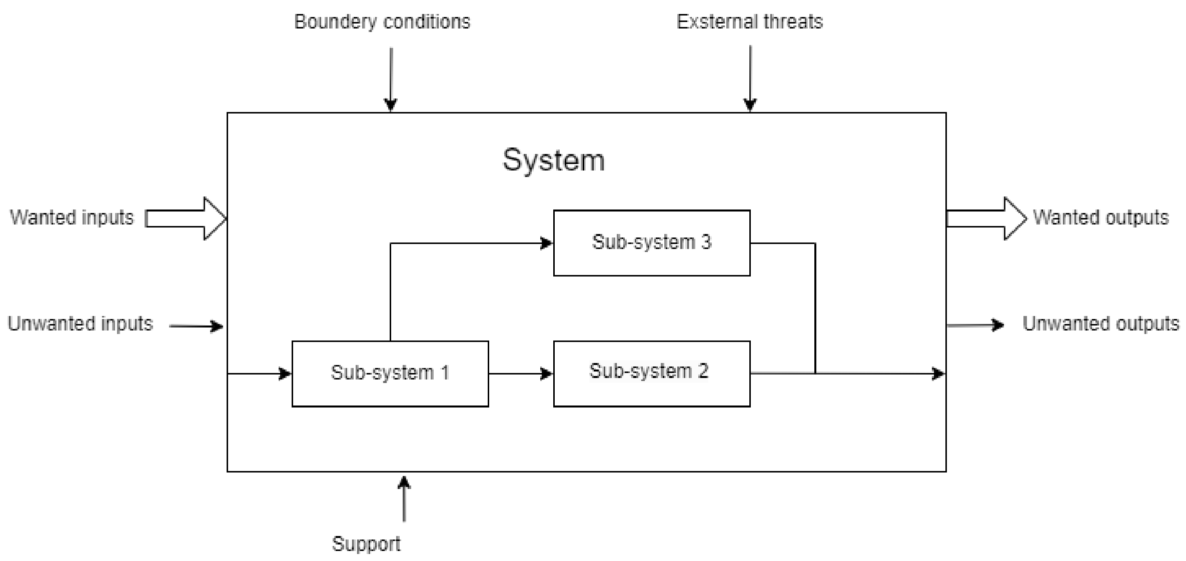


Figure 7 A technical system and its interfaces. [5, p. 75]

Functional failures: Finally, identify the ways in which the system might fail to function [5, p. 405] This is done through a FFA shown in the table below.

Maintainable Item	Operational Modes	Function Failure Analysis	
		Function	Failure

Table 1 FFA

Step 4: Critical Item Selection

In this step, all elements are subject to analysis and selection based on their level of criticality to the function of the system. These elements are commonly known as functional significant elements (FSI). While some items may be readily identified as function-critical, it is often necessary to adopt a formal approach to identify them. [5, p. 406]

Additionally, maintenance cost significant items (MCSI) have been identified, which are items that tend to have a high failure rate and repair cost. Maintenance significant items (MSI), can consist of FSIs, MCSIs, or both. The critical MSI elements are then subjected to analysis in the FMECA process in step 6, where a risk matrix is employed to identify them. [5, p. 406]

Figure 8 Significant Items

Step 5: Data Collection and Analysis

Many input data are needed for the various RCM procedures to be completed. All pertinent information is gathered and arranged, including information about operations, maintenance, and performance. The criticality of a functional failure is then assessed, and the best interval between PM tasks is then determined by the results of the assessment.

If the available data is insufficient, further options include consulting manufacturer advice, experience data from similar equipment, and expertise from those who regularly use or have in-depth understanding of the equipment. [5, p. 407]

Step 6: FMECA

FMECA, or failure mode, effects, and criticality analysis, is a qualitative analysis technique for evaluating how a given asset might fail and what the effect of the failure will be. Whilst studying the reliability of a system, completing an FMECA is usually the first step. Completing an FMECA is a straightforward process, but it's of importance to understand the system's purpose and under what constraints it must operate in. Also, the FMECA needs to be modified to fit the system and data at hand. The goal of the analysis is to determine the various ways an MSI can fail, why it fails, what its effects are, what consequences result from those effects, how failure is detected and how frequently one should perform maintenance tasks to maintain the assets' integrity. The FMECA should be integrated as early as the concept or design phase to assist in the selection of a design that fulfils the safety and reliability potential. [5, pp. 88,92,407]

The thesis takes into consideration the functional failures of some of the maintainable items of the BPSJ sub-system. The FMECA worksheet has been divided into two parts: safety and security, which both contain multiple terms which aim to describe each maintainable item, shown on the upcoming page. Below illustrates failure classifications utilized in the FMECA.

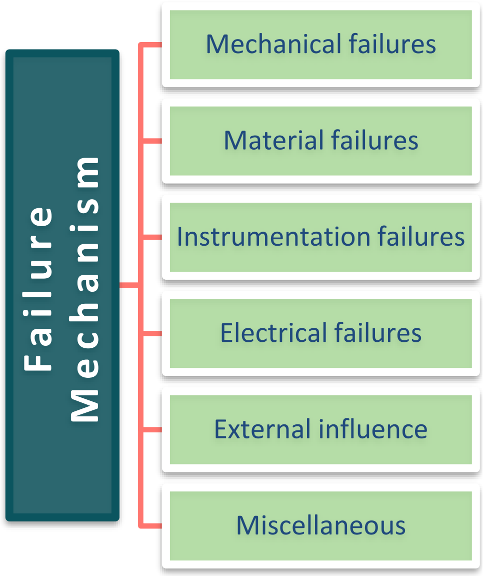


Figure 10 Failure mechanism classification ISO 14224:2016

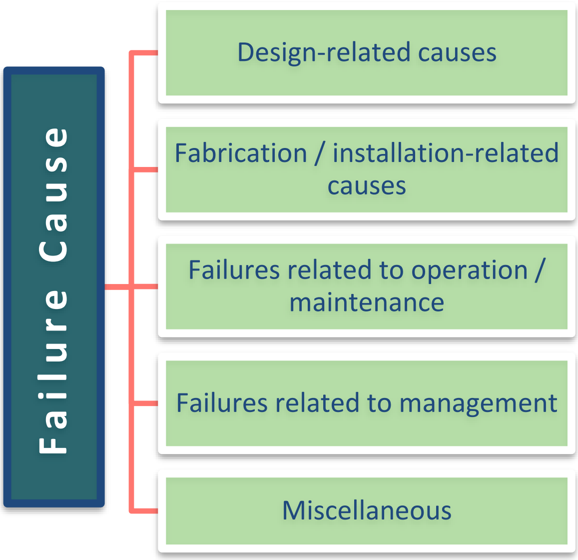


Figure 9 Failure cause classification ISO 14224:2016

Function Failure Analysis	Equipment Failure Profile
Function: The identification and documentation of the function or intended *effect* of maintainable items for each operational mode is a critical aspect of system maintenance. Each function is defined in a manner that accurately represents the item's purpose, emphasizing "what" is to be accomplished rather than "how." For instance, functions such as securing components together, handling predetermined torque, or disconnecting from the string are explicitly defined. Additionally, certain functions may include functional requirements, for example the BPSJ pressure relief valve's function of "opening valve" and its requirement of opening at the designed pressure of 11kpsi to ventilate hydraulic fluid. [5, p. 78] **Function failure:** The criteria for which the item does not meet its intended function. For example, if a components function is to maintain a specific pressure, it's functional failure would be unable/failure to maintain set pressure. **Vulnerability** (Weakness)**:** A description of the maintainable items' vulnerability or weakness. This understanding allows for a greater understanding of what may lead to component failure. An example of this may be physical-, design-, or manufacturing weakness. **Failure effect:** If an item fails to function as intended, what the effect of such failure would be is recorded.	**Equipment Failure cause:** Assessment of which circumstances may have led to failure. There may be multiple causes for a failure mode. The basis for failure cause is the ISO 14224:2016. Examples of failure cause may be improper material, expected wear and tear and installation failure. Failure mechanism and failure cause are closely related. Failure mechanism is related to the failure cause, but failure cause is aimed at uncovering the root cause of the failure. **Equipment Failure Mechanism:** Assessment of processes that may lead to failure of an item. The basis for failure mechanism is ISO 14224:2016. Examples of failure mechanism may be corrosion, fatigue, and deformation. **Equipment Failure Mode:** The identification and recording of potential failure modes for each maintainable item is an essential component of the maintenance process. A failure mode refers to a *fault* description that outlines how a fault is observed. Examples of potential failure modes may include failure to function on demand, failure to connect, or failure to open on demand. To describe the BPSJ maintainable items failure modes, the thesis relies on the failure modes outlined in Annex B.13 of the ISO 14224:2016 for Well Intervention Equipment. **Equipment Failure Characteristics:** assess if the failure took place suddenly (random), gradual degradation (ex. Wear, fatigue etc.) or if failure occurs over time/aging (probability of failure is age dependent).

Operational Attack	Accident	Environmental Attack	Incidence
Operational Hazard: Refers to any potential danger or risk that arises from the normal functioning or operation of a system or equipment. These hazards can arise due to various factors such as equipment malfunction, human error, inadequate maintenance, or environmental factors. **Operational Attack Mechanism: :** Refers to a specific method or technique used to exploit safeguards in a system in order to compromise its safety which may cause damage.	**Accident:** An explanation of the potential outcomes that may result from equipment failure during operation or otherwise. It describes the unintended events or series of events that can occur, potentially leading to death, injury, environmental damage, or material harm. [5, p. 599]	**Environmental Threat:** Refers to a possibility of harm that arises from external factors and exploits a vulnerability within a system, potentially resulting in unfavorable outcomes. **Environmental Attack Mechanism:** Refers to a specific method or technique used to exploit vulnerabilities in a system in order to compromise its security or cause damage.	**Incidence:** Refers to an event or series of events that have the potential to harm a system, compromising its normal operations and threatening its security. These events may be unwanted or unexpected and have the potential to cause damage or disruptions. Essentially, incidence is a manifestation of a security threat that has materialized and caused actual harm to the system. [15, p. 3]

Risk Analysis

Likelihood of Failure: A category ranking which accounts for the likelihood of a failure taking place with a category ranking of the failure's likelihood as "negligible" (level 1) to a likelihood of "expected" (level 5).

Consequence of Failure: The effect(s) or consequence(s) a failure mode has on an item's operation, functionality, or status. [5, p. 601] A category ranking of the failures worst potential consequence from a level A "slight" (lowest severity) to level E "massive" (highest severity).

Risk Class: Combining the consequence ranking and the likelihood ranking in a risk matrix gives an overall risk classification for the item. The items with the highest risk classifications will be selected for further analysis.

		Consequence of Failure				
		A - Slight	B - Minor	C - Moderate	D - Major	E - Massive
Likelihood of Failure	5 - Expected	2-Pass with Condition(s)	3 - Fail	3 - Fail	3 - Fail	3 - Fail
	4 - High	2-Pass with Condition(s)	2-Pass with Condition(s)	3 - Fail	3 - Fail	3 - Fail
	3 - Medium	1 - Pass	2-Pass with Condition(s)	2-Pass with Condition(s)	2-Pass with Condition(s)	3 - Fail
	2 - low	1 - Pass	1 - Pass	2-Pass with Condition(s)	2-Pass with Condition(s)	2-Pass with Condition(s)
	1 - Negligible	1 - Pass	1 - Pass	1 - Pass	1 - Pass	2-Pass with Condition(s)

Table 2 Risk Matrix

Step 7: Selection of Maintenance Actions

Decision logic guides the analyst through a question-and-answer process to determine if preventive maintenance (PM) activities are appropriate for each dominant failure mode identified in the Step 6 FMECA. This involves assessing whether it is more beneficial to carry out PM tasks or to let the item run to failure and then perform corrective maintenance (CM) tasks. There are three main reasons to conduct PM, which are to prevent failure from occurring, detect the onset of failure and to discover hidden failures. There are several maintenance tasks which may then considered, such as: Scheduled on-condition task, scheduled overhaul, scheduled replacement, scheduled function test and run to failure [5, p. 410]

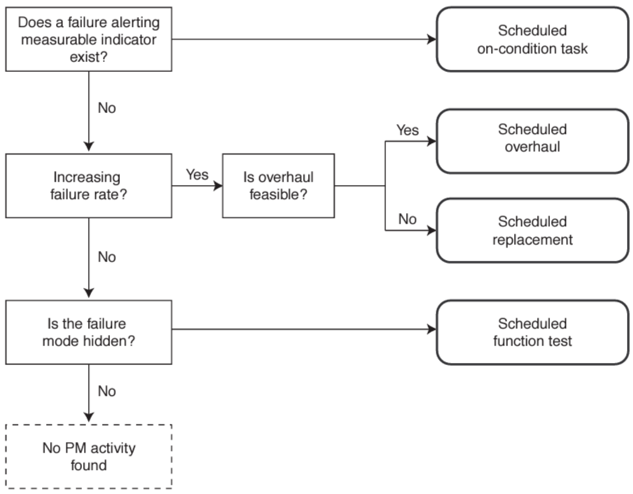


Figure 11 RCM Decision Logic [5, p. 412]

Step 8: Determination of Maintenance intervals

The determination of the most suitable interval for preventive maintenance tasks is a challenging decision, since it requires consideration of the failure rate function, the potential consequences of failure, and the cost of implementing preventive maintenance measures. Maintenance tasks are typically grouped together and performed simultaneously or in a specific order, resulting in maintenance intervals that are not optimized for each individual item, but rather for the system as a whole. [5, p. 412]

When conducting an analysis, the availability of reliable data may be initially limited. In such cases, a Reliability Centered Maintenance (RCM) approach can prove highly advantageous, serving as the foundation for a methodical analysis that documents the initial decisions made. This documentation can subsequently be updated based on the availability of operational experience data. The key advantage of employing an RCM is its ability to incorporate maintenance experience feedback into the analysis process, providing a comprehensive and effective maintenance strategy.

Process updating should be focused based on time perspectives, such as: short-term interval adjustments, medium-term task evaluation and long-term revision of the initial strategy. System significant failures that occur should be compared to the FMECA, and if necessary, the relevant part of the RCM should be revised. [5, p. 414]

- The short-term update will only affect step 5-8 in the RCM process.
- The medium-term update should assess the maintenance actions in step 7 in the RCM process. Maintenance experience analysis could lead to detection of failure causes that may be significant which were not considered in the original analysis, this will require a change to step 6: FMECA.
- The long-term revision should assess all the RCM analysis steps. The system alone is not sufficient to analyze, it is necessary to analyze the entire plant in relation to it's the world around it (contracts, laws, etc.).

3.3 Cause-and-effect analysis

In order to identify the root cause of an undesired event or problem, a Cause-and-effect analysis is commonly utilized to structure the identification process. This analysis entails identifying all possible contributing factors and organizing them in a systematic manner. However, it is important to note that the analysis itself does not provide definitive evidence of the actual causes, as these can only be determined through empirical testing of hypotheses based on factual evidence. Typically, the information gathered through this analysis is organized into a Fishbone diagram to facilitate understanding and communication of the various contributing factors. [IEC/ISO 31010 [16]]

In this thesis the cause-and-effect Fishbone diagram will be used. It is also known as the Ishikawa diagram, which was developed by Kaoru Ishikawa in 1943. The identification and descriptions of all potential causes are presented in a way that resembles the skeleton of a fish, as illustrated in the picture under. The reason for choosing this diagram instead of a fault tree is that Fishbone does not have the same binary restrictions as a fault tree, meaning that the Fishbone diagram is more flexible to utilize.

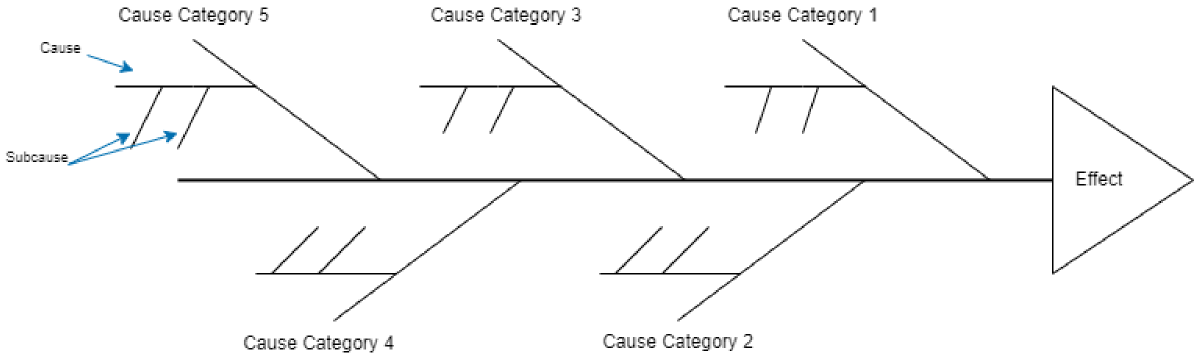


Figure 12 Fishbone diagram - IEC/ISO 31010 [16]

To construct a cause-and-effect diagram it is customary to position the effect of the failure under consideration at the right extremity of the diagram, serving as the "head of the fish." A central spine, indicated by a thick line, is then drawn pointing towards the head from the left side. The main classifications of potential causes are then illustrated as bones attached to the spine. When assessing technical systems, it is common to employ the following five categories as cause classifications: 1. Manpower 2. Methods 3. Materials 4. Machinery 5. Environment. [5, p. 106] Supplementary causes may also be incorporated by incorporating a new line to indicate the subcategory. [17, p. 18]

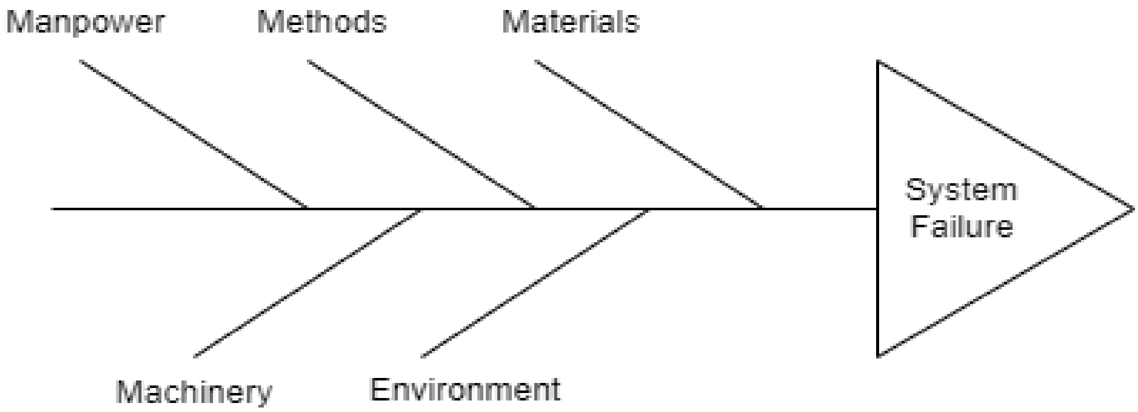


Figure 13 Cause Categories

3.4 Safety and Security

This thesis aims to improve the traditional risk evaluation method by adding security to the concept of safety. Safety, security, and survivability engineering are related disciplines that focus on protecting valuable assets from harm caused by accidents or attacks. [8]

A part of the aim is to investigate the basis for expanding the already established method for implementing FEMCA. By doing this, new ideas and innovations on the traditional FMECA will be presented. These changes have been implemented by incorporating the concepts of vulnerability, safety, and security into the thesis FMECA analysis. By doing so, a more comprehensive risk assessment has been completed which may have the subsequent effect of improving overall system performance. The FMECA has been divided into two parts: *safety* and *security*. Additionally, a detailed assessment of the vulnerability of each maintainable item is included.

In recent years, the field of cybersecurity has become increasingly relevant and important as technology continues to advance. “Safety, security, and survivability engineering are three very closely related disciplines that could greatly benefit from a widespread recognition of their similarities and differences.” [8] It has become apparent that lessons learned from the cybersecurity industry can be applied to other fields, including the further development of FMECA method. FMECA is a widely used method for identifying and prioritizing potential failure modes in a system. By drawing inspiration from the cybersecurity industry, we have been able to improve the FMECA method and make it more comprehensive.

One of the key concepts the team has implemented from the cybersecurity industry is the concept of vulnerability. “Survivability vulnerability is a weakness in the system that increases the likelihood that an accident or a successful attack will occur and stop an essential service from being provided.” [8] To implement this concept to a mechanical system, vulnerability refers to the potential for a system to fail due to a specific failure mode. Vulnerability is a quality of a system or of a maintainable item that contributes to a weakness, which may lead to component failure. An example of this may be physical weakness, manufacturing weakness, and so forth. By incorporating the concept of vulnerability into our FMECA analysis, the team is better able to identify and prioritize potential failure modes.

Vulnerability can manifest in a mechanical system through various failure causes, such as design, manufacturing, assembly, or use. To illustrate this, consider the example of a tangential gear. The teeth of the gear represent a point of vulnerability, and their failure can ultimately result in system failure. The following table summarizes the connection between the different failure causes and the resulting vulnerabilities in the system:

Failure	Vulnerability	Failure cause	Description
The teeth break	The teeth	Design	The teeth may be undersized and will not withstand the force applied in the system.
The teeth break	The teeth	Manufacturing	Incorrect heat treatment gears need to be heat-treated to achieve the right level of hardness and strength.
The teeth break	The teeth	Assembly	If the gears are not installed properly, they can experience uneven stress, leading to failure.
The teeth break	The teeth	Use	Over time, the constant meshing of gears can cause wear and tear, which can lead to failure. This is particularly true in high-load applications or when the gears are not lubricated properly.

Table 3 Vulnerability Example

Safety focuses on unintentional events while security also focuses on threats coming from outside the system, often caused by malicious parties as mentioned in the paper *Safety vs. security?* [15] When integrating these concepts into the FMECA method, it is crucial to understand the difference between safety and security. Safety in cybersecurity relates to the extent to which accidental harm is prevented, detected, and reacted to. Contrarily, security refers to the measures taken to protect a system from intentional harm. By implementing both safety and security measures in an FMECA analysis, we can create a more comprehensive risk assessment and improve overall system performance. These concepts are implemented in a mechanical system with the definitions below.

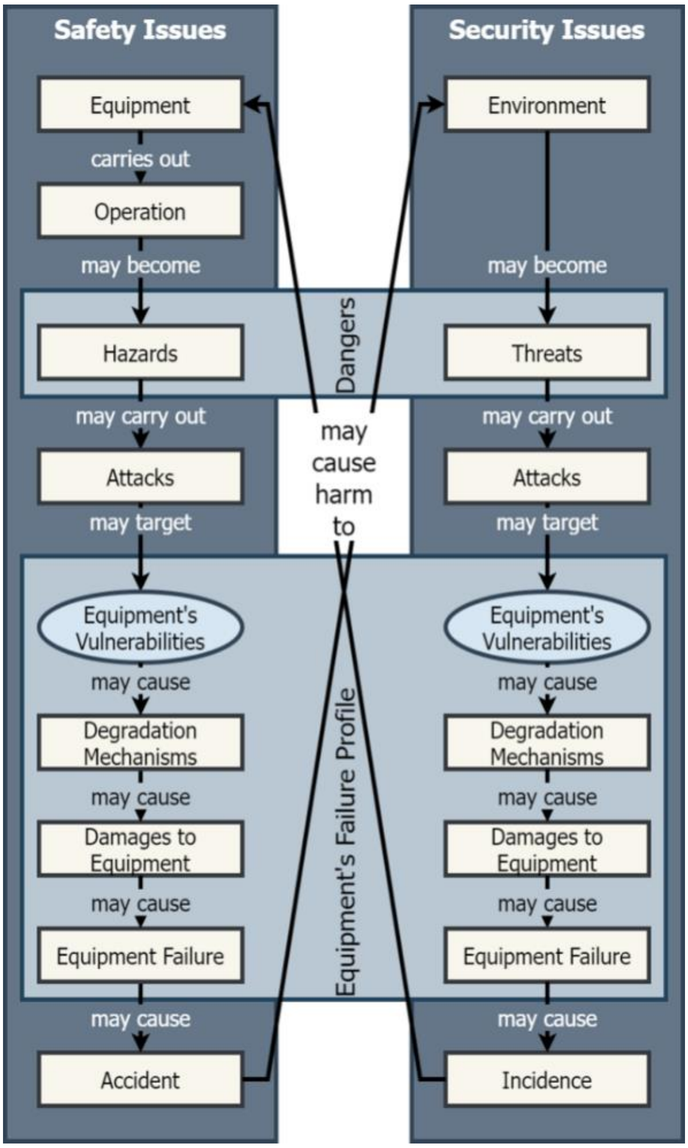


Figure 14 Safety and Security [18]

Safety is the degree to which hazard is prevented, detected, and reacted to. A hazard is an inherent quality of a system that possesses the potential to trigger vulnerabilities within that system, leading to its failure.

Security is the degree to which a threat is prevented, detected, and reacted to. A threat is an inherent quality of the environment that possesses the potential to trigger vulnerabilities within the system, leading to its failure. [18]

The safety part of the FMECA method involves accidents and the security part involves attacks. However, accidents may result in security vulnerabilities which may be exploited by attacks, which will then result in consequences which may fall within the realm of security. In the same manner, attacks may cause safety hazards that result in accidents.

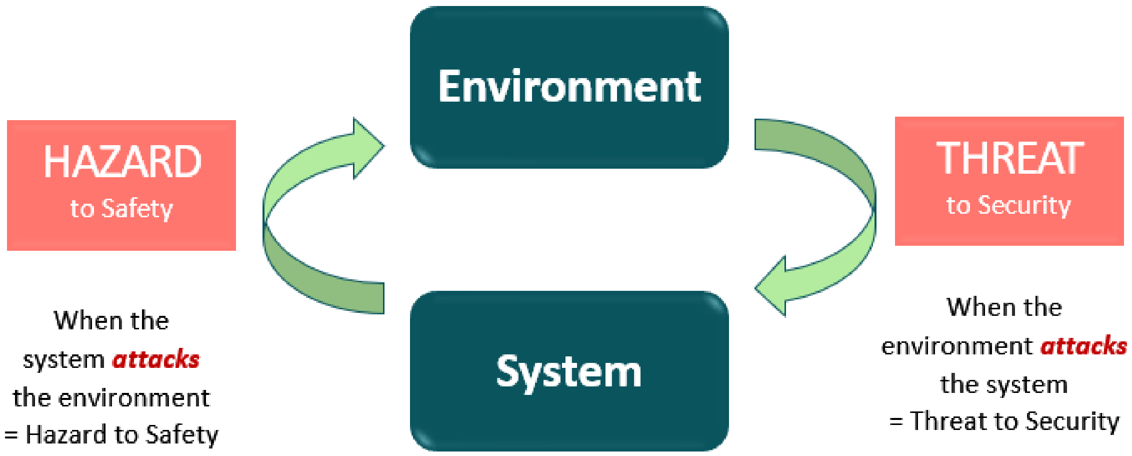


Figure 15 Environment System

The implementation of safety and security measures in the FMECA method leads to two distinct cycles, each triggered by a unique factor that results in functional failure. The first scenario involves a safety issue, in which the equipment or system initiates an attack on the environment surrounding the underlying hazard. This results in the interference of function failure and subsequent re-implementation of the function failure profile. The second scenario pertains to a security issue, wherein the environment attacks the equipment or system, leading to the interference of function failure and the implementation of the function failure profile.

To summarize, security is a concept used in the realm of cybersecurity when assessing risk. However, the safety and security disciplines share similarities in their focus on preventing or reducing hazards and threats, which is crucial in protecting valuable assets and ensuring the continued functionality of essential services. By implementing the aspects of security to the analysis it aims to become a more thorough assessment of the asset (BPSJ), preventing or reducing hazards and threats. Safety, security, and survivability engineering contribute to the overall protection of the asset.

4. Case Study of BSPJ

The purpose of this chapter is to introduce the focus of the analysis in this report, namely the BPSJ sub-system. The chapter details how the RCM steps were applied to the BPSJ, followed by an in-depth examination of specific deficiencies observed in the tool, such as corrosion and deformation. To facilitate a closer analysis of the potential causes of failure, fishbone diagrams were implemented as well.

4.1 The sub-system - Below Packer Safety Joint

As previously noted in the introduction, the BSPJ tool finds application in offshore drilling operations, particularly in oil reservoirs located in deep water fields. These reservoirs are often geographically remote, necessitating access via drilling platforms or floating production facilities. Given the intricate and demanding nature of deepwater drilling, effective exploration and production of these reserves mandates sophisticated technology, technical proficiency, and substantial financial resources. BSPJ serves as a component of the perforation string employed in the perforation of oil wells. [10]

The conditions that the BPSJ tool operates in are in a heavy corrosive brine, high pressures up to 103 MPa, and temperatures that can be anywhere from freezing to 177 °C. These conditions combined with depths of approximately 6096 meters, are some of the most extreme operating conditions that a tool is made to endure. [19]

The process of perforating oil wells involves the creation of small openings in the casing or wellbore to enable the flow of oil and gas into the wellbore. Typically, this is achieved using a perforation gun, which deploys explosive charges to create holes in the casing and surrounding rock formation. During this process pressure differentials occur, leading to equalization where the flow of debris such as sand, chalk, and stone, may flow back towards and into the perforating tool. This influx of debris can clog the steel pipe and cause the perforating gun to become stuck. This represents a significant risk, as the tool string may become lodged several kilometers down the borehole, potentially resulting in the loss of millions of dollars' worth of equipment, and endangering oil wells that may be worth several hundred million dollars. [10]

Given the potential consequences of a stuck tool string, it is essential to salvage as much of the tool string as possible. BSPJ is, therefore, equipped with two mechanisms that act as safety guards in the event of this occurrence. These mechanisms will be described in detail below.

Tension Release

The first way to address this issue is the safety joint feature that allows it to give a shock or a yank to the string when it yields, making this one of the primary functions of the tool. To make tension and pull the string, the rig tower uses a hydraulic system. Making this tool passive, responding only to external forces.

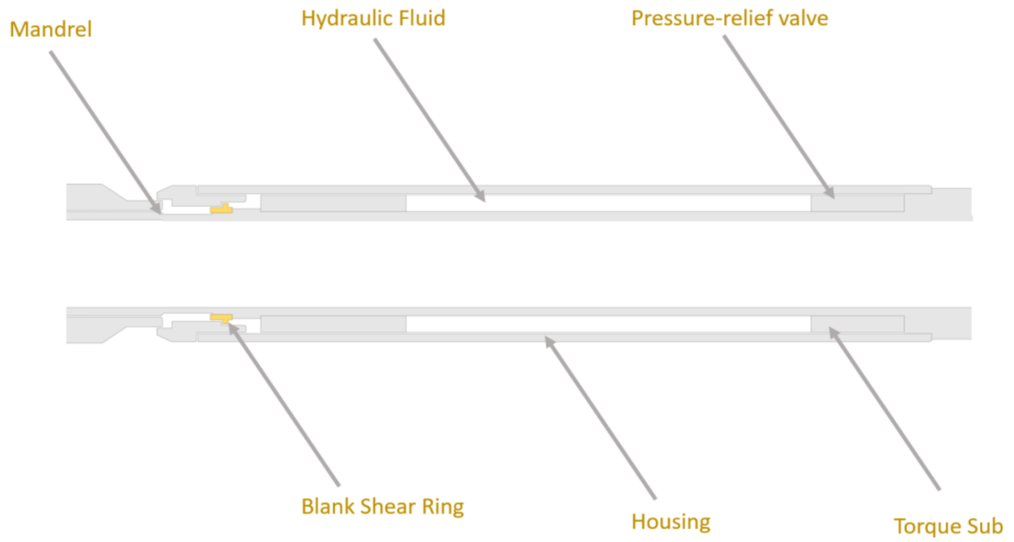
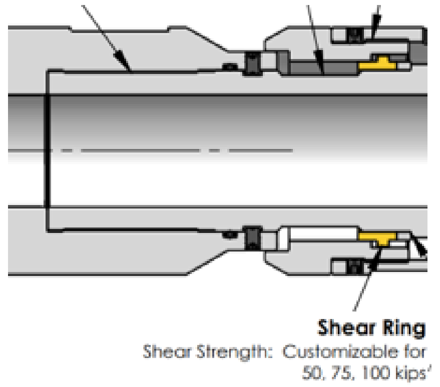


Figure 16 BPSJ

The hydraulic system under consideration comprises of the housing, which serves as a hydraulic cylinder, and a mandrel and torque sub, which functions as the piston. The system includes a reservoir filled with hydraulic fluid that occupies the space between the housing and the mandrel.



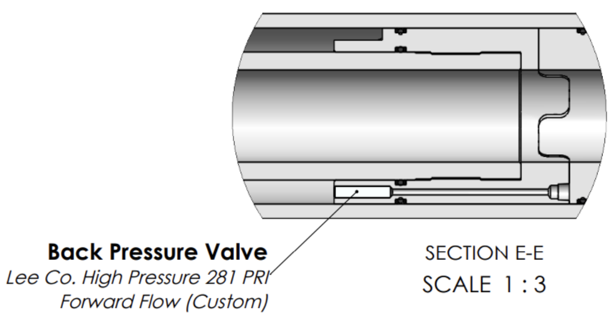


Figure 18 Shear Ring

Figure 17 Back Pressure Valve

The activation mechanism for the tool is a shear ring, a specialized component designed to provide a controlled breaking point. Once the ring is subjected to sufficient force from the oil rig, it reaches its shear limit and fractures, allowing the tool to expand. As a result, the teeth of the Torque sub disengage, enabling it and the mandrel to stroke open.

The upward movement of the Torque sub and mandrel creates pressure in the system's hydraulic fluid reservoir, which continues to build until it reaches the set pressure of the pressure-relief valve, at which point the valve opens. Hydraulic fluid then flows into the space between the Torque sub and the Bottom sub, equalizing the pressure. This process repeats several times as the rig continues to pull the string, providing the string with multiple yanks.

Step 1: The strings are hydraulically lifted by the oil rig. The weight from the perforating gun creates so much tension that the shear ring break and the tool is activated.

Step 2: The tool expands increasing the pressure inside the hydraulic fluid reservoir to the point that the backpressure valve opens and causing yank a on the string.

Step 3: This happens repeatedly until it is no longer possible to build enough pressure in the reservoir to open the back pressure valve again.

Figure 19 Tension Release Process

Disconnecting

The Disconnecting mechanism is the last resort to save the equipment if the string is stuck. It is designed to activate after the Tension Release mechanism fails to work. Once activated, the Disconnecting mechanism ensures that all the equipment located above the BSPJ is saved. Unlike the Tension Release mechanism, not all the equipment is saved in this process. Therefore, the Disconnecting mechanism is a last resort measure that is put in place to protect the assets.

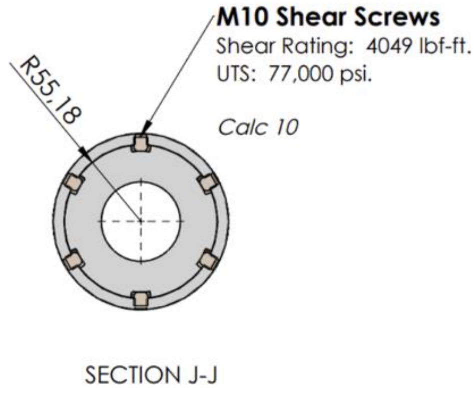


Figure 20 Shear Screws

To understand the Disconnecting mechanism, it is important to have some background knowledge about the whole system in which it operates. The string system is a complex mechanical setup, but an important element for exactly this is the torque rotation. The rotation is applied from the oil rig and causes the string to rotate clockwise when viewed from above. This is also known as a right-hand rotation. It is important to note that this rotation can occur without any part of the string becoming loose or disconnected. This is a critical feature of the design of the Disconnecting mechanism.

Figure 21 Disconnecting Mechanism

The design quality of right rotation in the String system makes it possible to activate the Disconnecting mechanism with a left-hand rotation. When it becomes necessary to activate the Disconnecting mechanism, the entire string is rotated to the left using the torque generated by the oil rig. This rotational movement applies shear forces to the six shear screws located around the perimeter of the housing, which are responsible for holding the housing and sub-base together. After seven turns, the shear forces exceed the predetermined threshold of the screws, causing them to break and resulting in the separation of the housing and bottom sub. The implementation of this separation mechanism enables the efficient retrieval of the string from the well to the rig. This operation ensures the preservation of both the equipment and the well, resulting in potential savings of several hundred million dollars.

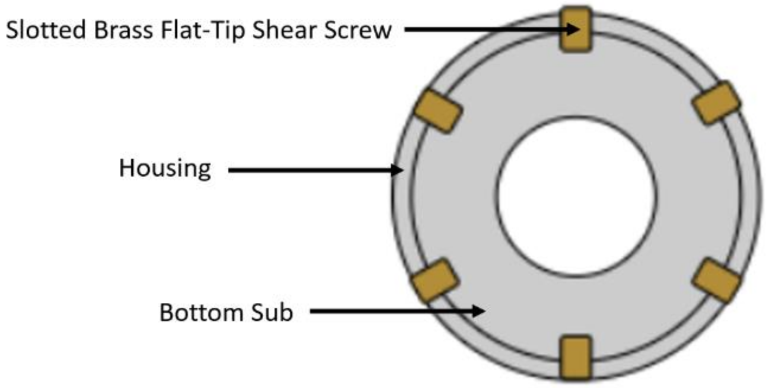


Figure 22 Components in disconnecting function

4.2 RCM of the BSPJ

This sub-chapter details the practical completion of RCM steps for the BPSJ sub-system. It covers the analysis of the sub-system, identification of failure modes and their consequences, and an evaluation- and implementation of recommended maintenance task actions. The aim is to provide the reader with a clear understanding of the RCM process and its outcomes.

Step 1: Study Preparation

The RCM was initiated with the study preparation stage, where the scope of work was defined, as outlined in Chapter 1 of this thesis. To effectively define the scope of work for this project, meetings were conducted with representatives of Entech and the designer of the BPSJ during the initial phase of the project. These meetings provided valuable insights into the BPSJ and its place within a broader context. Additionally, discussions were held regarding the problems faced with a similar well intervention tool in their assortment.

Throughout the project, a comprehensive understanding of the tool's function and components was attained through various resources. This includes ISO 14224:2016 and IEC/ISO 31010 standards. The team have based the tool's design on the drawing presented in appendix B, while also considering its place within the larger system by analyzing the drawing presented in appendix C. Additionally, the team consulted the expert opinions of the professionals that designed and work with the tool regularly. As well as searching for insight and information from credible books such as "Developments in Petroleum Science, Volume 56 - Well Completion Design". Furthermore, through our research, the team gained insight into the workings of maintenance concepts, drawing on the knowledge provided by the books "System Reliability Theory" and "Maintenance and Reliability Best Practices", as well as other relevant articles. This understanding equipped the team with the necessary groundwork to move forward confidently with the next step in the project.

Step 2: System Selection and Definition

After the scope of the work was defined it was made possible to systematize the information and decide on what part of the system to study. A technical hierarchy was created for analysis to gain a greater understanding of each component. After creating a hierarchy, it gave the team the clarity to conduct the analysis on the maintainable item level of the BPSJ sub-system.

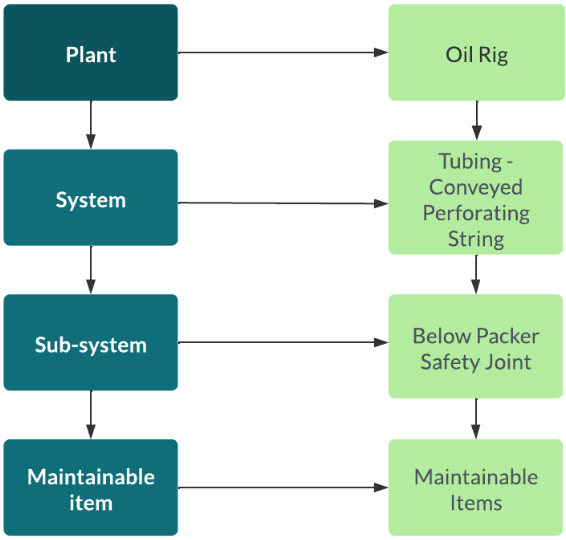


Figure 24 Hierarchy

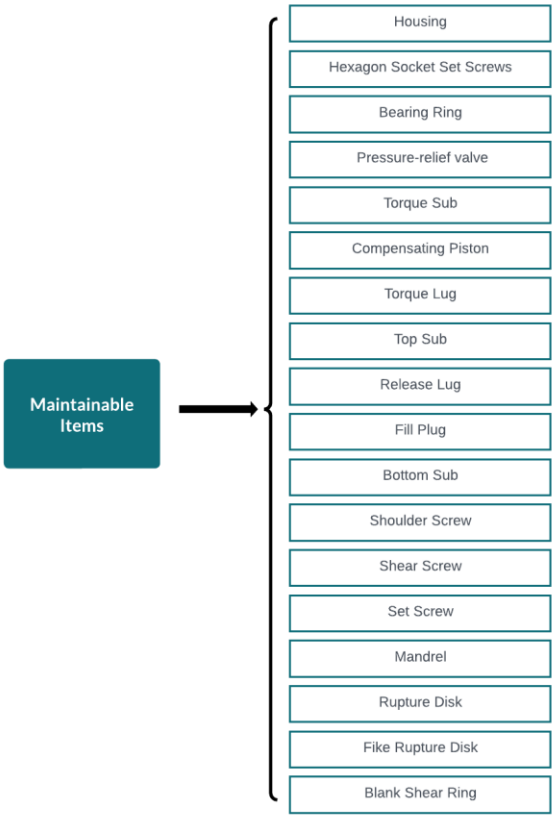


Figure 23 Maintainable Items

Step 3: Functional Failure Analysis (FFA)

The team employed analytical tools to help clarify and better understand the objective of this step, which is to identify system functions, interfaces as well as functional failures.

Firstly, identification of the different functions of the system was recognized with the assistance of a FAST diagram. Where the main function of the sub-system was identified (on the left side) such as "act as a safety guard." Then the question of how this function can be achieved is inquired, and a list of the necessary functions is placed towards the right side of the diagram. We continue asking "*how*" going towards the right side for each function, until we have identified all the necessary functions and achieved the level of detail needed to fully understand the sub-system. Going from right to left one should be able to ask "*why*" and understand the purpose of the function. [5, pp. 80-81]

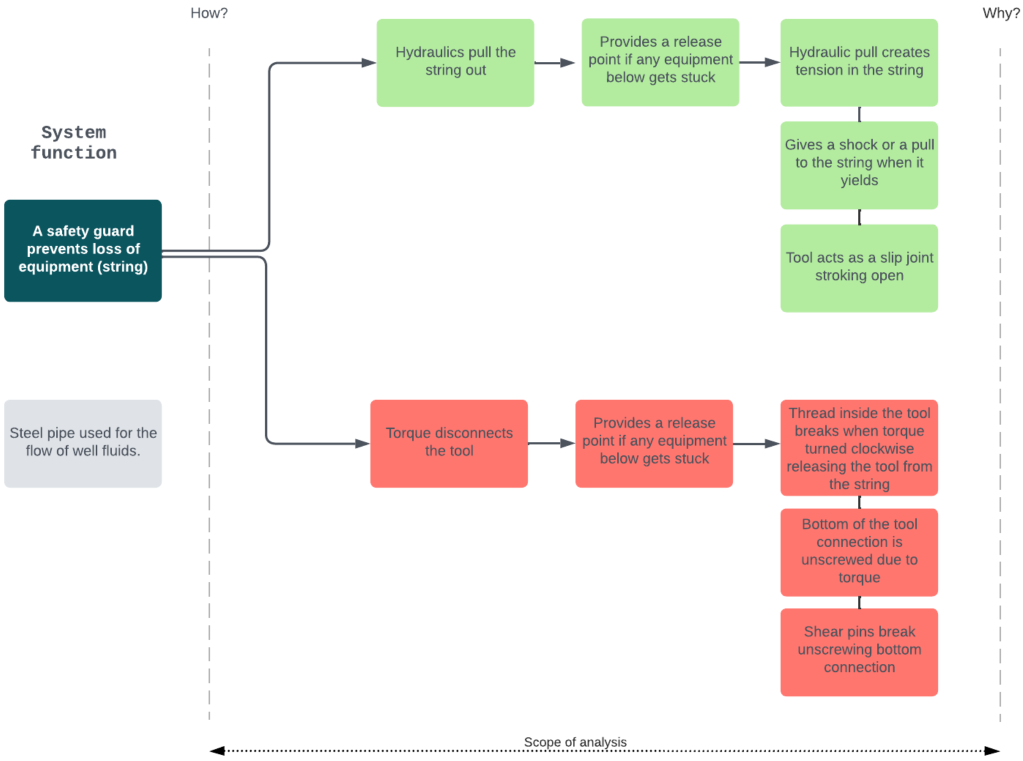


Figure 25 System Function

Secondly, a figure was created to illustrate how the BPSJ interfaces with other systems as well as with its environment. It is the study of how interfaces influence the TCP string system. In the illustration the BPSJ represents the “sub-system 27”, “sub-system 1-26” represents the equipment on the TCP string above the BPSJ, and “sub-system 28-37” represents the equipment below the BPSJ on TCP string. This type of representation acquires a greater understanding of the wanted and unwanted inputs and outputs of the system, as well as which boundaries it operates under, and lastly the external threats which may have an adverse effect on the system.

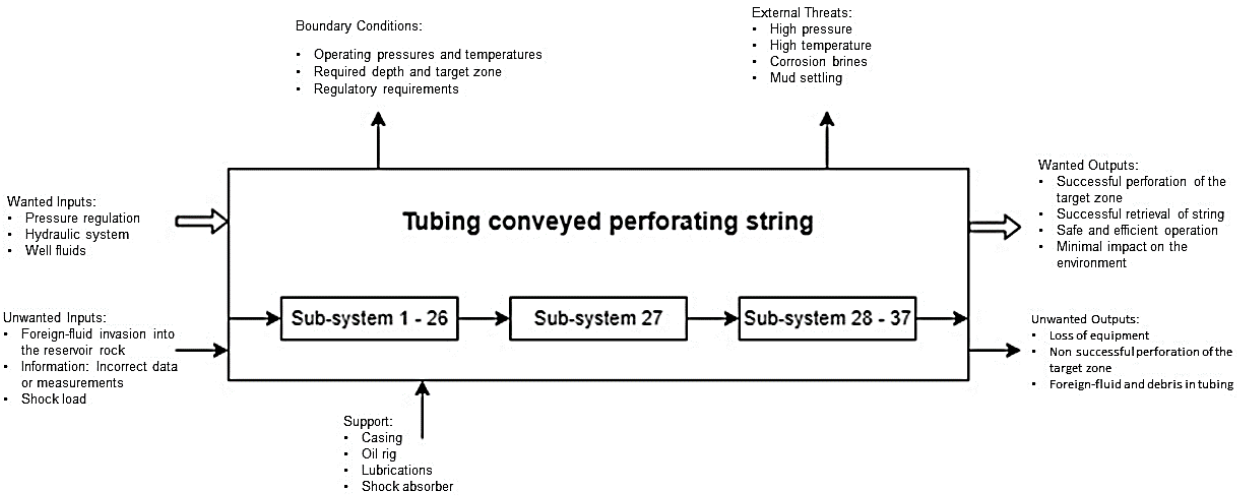


Figure 26 System Interface

In the third step, a Functional Failure Analysis (FFA) was conducted on the maintainable items of the BPSJ sub-system. The purpose of the FFA was to identify the function(s) of each maintainable item, as well as potential functional failures that could occur during its mode of operation. The results of the FFA were documented in an Excel worksheet, where each maintainable item was assigned its own column, as illustrated in Table 1 below. The worksheet captured information on the mandrel being analyzed, including its operational modes, function, and potential failure modes (functional failure). To view the FFA on the additional maintainable items see Appendix F.2.

Maintainable Item	Operational Modes	Function Failure Analysis	
		Function	Failure
Mandrel	Preparation: Installing in the String	Not relevant	Not relevant
	Operation: Normal	To separate the pressure zones inside the housing	Incorrect pressure in reservoirs
	Operation: Tension Release	To separate the pressure zones inside the housing	Incorrect pressure in reservoirs
	Operation: Disconnecting	Load-bearing element	Not strong or stable enough to withstand the loads or stresses
	Retrieval: String from Well	Load-bearing element	Not strong or stable enough to withstand the loads or stresses
	Transportation and Storage:	Maintain component integrity	Component integrity compromised

Table 4 FFA Mandrel

The objective of the FFA was to evaluate the potential risks associated with the operation of the BPSJ sub-system and its maintainable items. By identifying potential functional failures, the FFA provided insights into areas that required attention and mitigation to prevent failures that could cause downtime or cause operational hazards.

The maintainable items analyzed in the FFA were considered in six different operational modes which are as follows:

1. Preparation: Installing in the String
2. Operation: Normal
3. Operation: Tension Release
4. Operation: Disconnecting
5. Retrieval: String from Well
6. Transportation and Storage: Time Between Campaigns

To conduct a thorough analysis and minimize the risk of overlooking significant item functions and associated failure modes, it is important to consider different operational modes. By considering the various modes in which the BPSJ operates, a more comprehensive analysis can be conducted, which can help identify failure modes that are specifically related to certain operational modes. This approach creates a strong foundation for identifying and mitigating potential failure modes, ensuring the safe and effective operation of the BPSJ under a variety of conditions. [5, p. 79]

Step 4: Critical Item Selection

Based on the functional failures that were identified in the previous step, the objective of this step is to identify which of the maintainable items are potentially critical. To accomplish this, a Critical Item Selection process is carried out. During this stage, all items are evaluated in terms of their functional significance as well as maintenance cost significance. Items that meet the criteria for being Maintenance Significant Items (MSIs) are identified and analyzed further in the subsequent step. The FSIs (Functional Significant Item) and MCSIs (Maintenance Significant Item) were identified without a formal analysis due partly to the fact that the BPSJ is not an extremely complicated sub-system, but also due to the lack of reliability data. Furthermore, if an item was deemed either FSI or MCSI or both, the item is denoted MSI.

Upon completion of the Critical Item Selection process, a total of six Maintenance Significant Items were identified. These items include the Bottom Sub, Mandrel, Compensating Piston, Blank Shear Ring, Slotted Brass Flat-Tip Shear Screw, and Torque Sub. These items will be subjected for further analysis in the upcoming step to identify potential root causes of their functional failures and to develop appropriate corrective actions.

Description	Critical Item Selection		
	Functional Significant Item (FSI)	Maintenance cost significant item (MCSI)	Maintenance significant item (MSI)
Bottom Sub	Yes	Yes	Yes
Fill Plug	No	No	No
Release Lug, BPSJ	No	No	No
Torque Lug	No	No	No
[A9569-2] Fike Rupture Disk,	No	No	No
Compensating Piston	Yes	Yes	Yes
M10 x 1.5 x 12 Slotted Brass Flat-Tip Shear Screw - C675 Manganese Bronze	Yes	No	Yes
Mandrel BPSJ	Yes	Yes	Yes
Blank Shear Ring, BPSJ	Yes	No	Yes
Top Sub	No	No	No
M5 x 0.8 Thread-Locking Shoulder Screw	No	No	No
Torque Sub	Yes	Yes	Yes
M8 x 8 - DIN 916 Hexagon Socket Set Screws With Cup Point	No	No	No
Housing, BPSJ	No	No	No
Bearing Ring	No	No	No
Pressure-relief valve, 10000psi, 0.281" dia	No	No	No
Tension Sub	No	No	No
M8 x 1.25 x 12 Alloy Steel Cup-Point Set Screw	No	No	No

Table 5 Critical Item Selection

Step 5: Data Collection and Analysis

When devising a maintenance program for a novel sub-system such as the BPSJ, there is typically a small number of reliability data available. Consequently, the project team had to rely on expert opinions from individuals involved in the design of the BPSJ, as well as feedback from Entech's customers who utilize the tool. The team also analyzed various resources, such as assembly drawings, string diagrams, quality alert reports, equipment BOM lists, Entech's' preventive maintenance manual, as well as photographs. However, since the availability of reliability data was limited, all conclusions drawn from the results were based on subjective expert opinions, rather than mathematical analysis.

Step 6: FMECA

In the context of Failure Mode, Effects, and Criticality Analysis the items that have been identified as critical are subjected to further analysis. Each of these items undergoes a comprehensive evaluation, with a criticality assessment conducted for both safety and security considerations. The FMECA worksheet provides an overview of the potential failure modes associated with these items, as well as any corresponding functional failures. The analysis assesses the various ways an MSI can fail, why it fails, what its effects are, what consequences result from those effects, how failure is detected and what types of maintenance tasks should be completed to maintain the components integrity. The MSI items from step 4 were subjected to a criticality analysis, in which a risk classification of 1-Pass with condition(s) or 2-Fail, a selection of maintenance actions was recommended. Furthermore, the components which were deemed a risk classification of 2-Fail, went on for further analysis seen in Chapter 4.3 Quality Alert Rapport.

To further illustrate the findings of this analysis, a condensed version of the completed FMECA worksheet is illustrated below, firstly the safety analysis and thereafter the security analysis. The complete analysis is included in appendix F.4-F.15.

Safety		Operational Attack		Equipment Failure Profile				Accident	Environmental Attack		Incidence
Item	**Mode**	**Operational Hazard**	**Operational Attack Mechanism**	**Equipment Failure Cause**	**Equipment Failure Mechanism**	**Equipment Failure Mode**	**Equipment Failure Characteristics**		**Environmental Threat**	**Environmental Attack Mechanism**	
Bottom Sub	1	Mechanical Physical	Mechanical Physical	Design Manufacturing Usage	1.3 Clearance / alignment failure 1.4 Deformation 2.5 Breakage	FCO	Aging, Gradual	Deformation of equipment connection points and leakage.	Mechanical: deformation hinder the placement/setting of tool to the string.	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Deformation can halt operations by disconnecting from lower equipment.
	2	Mechanical	Mechanical	Design Manufacturing Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FTD	Sudden, Aging, Gradual	The tool strings fail to ascend from the well	Mechanical: Hinder other components' functionality, inhibiting task execution.	Weak mechanical properties require other components to share workload, preventing intended function alone.	The tool strings fail to ascend from the well
	3	Mechanical	Mechanical	Design Manufacturing Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FTD	Sudden, Aging, Gradual	The tool strings fail to ascend from the well	Mechanical: Hinder other components' functionality, inhibiting task execution.	Weak mechanical properties require other components to share workload, preventing intended function alone.	The tool strings fail to ascend from the well
	4	Mechanical	Mechanical	Design Manufacturing Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FTD	Sudden, Aging, Gradual	The tool strings fail to ascend from the well	Mechanical: Hinder other components' functionality, inhibiting task execution.	Weak mechanical properties require other components to share workload, preventing intended function alone.	The tool strings fail to ascend from the well
	5	Not Relevant	Not Relevant	Not Relevant	Not Relevant	Not Relevant	Not Relevant	Not Relevant	Not Relevant	Not Relevant	Not Relevant
	6	Mechanical	Mechanical	Design Manufacturing Usage	2.2 Corrosion 2.5 Breakage	FCO	Sudden, Aging, Gradual	Mobility limits of tool strings can stop well operations.	Mechanical: Hinder other components' functionality, inhibiting task execution.	Weak mechanical properties require other components to share workload, preventing intended function alone.	Tool string mobility restrictions can cause disconnection from lower equipment and halt operations.
Mandrel	1	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	2	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage 2.6 Fatigue	FCO	Sudden, Aging, Gradual	High pressure differential within the chamber exerts a significant amount of force, which can cause the mandrel to become damaged	Mechanical: Hinder other components' functionality, inhibiting task execution.	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Failure of Operation Mode: Tension Release
	3	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage 2.6 Fatigue	FTD	Sudden, Aging, Gradual	The absence of pressure results in the failure to execute the Tension Release	Mechanical: Hinder other components' functionality, inhibiting task execution.	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Partial loss of equipment (bottom sub and all equipment below)
	4	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage 2.6 Fatigue	FCO	Sudden, Aging, Gradual	Application of torque forces can lead to damage of the mandrel	Mechanical: Hinder other components' functionality, inhibiting task execution.	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Partial loss of equipment (bottom sub and all equipment below)
	5	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage 2.6 Fatigue	FCO	Sudden, Aging, Gradual	Application of forces related to uninstallment of the tool can lead to damage of the mandrel	Mechanical: Hinder other components' functionality, inhibiting task execution.	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Partial loss of equipment (bottom sub and all equipment below)
	6	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage 2.6 Fatigue	FCO	Sudden, Aging, Gradual	Application of unexpected forces (mishandling) can lead to damage of the mandrel	More costly and time consuming maintenance / repair	Longer lead times	Delayed operation between campaigns
Compensating Piston	1	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	2	Physical	Physical	Design Manufacturing	1.1 Leaking 2.6 Fatigue	STD	Sudden, Aging, Gradual	Leak of hydraulic fluid	Lack of pressure	Insufficient amount of hydraulic fluid	Failure of Operation Mode: Tension Release
	3	Mechanical Physical	Mechanical Physical	Design Manufacturing Usage	1.1 Leaking 1.4 Deformation 2.6 Fatigue	STD	Sudden, Aging, Gradual	Deformation of equipment connection points and leakage of hydraulic fluid.	Physical: Misalignment	Mechanical: deformation hinder the placement	It inhibits functionality and additional tools
	4	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	5	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	6	Mechanical	Mechanical	Design Manufacturing	1.1 Leaking 2.6 Fatigue	STD	Sudden, Aging, Gradual	Application of unexpected forces (mishandling) can lead to damage of the compensating piston.	More costly and time consuming maintenance / repair	Longer lead times	Delayed operation between campaigns
Blank Shear Ring	1	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage	STD	Sudden, Aging, Gradual	Relase before intended	Mechanical: Excess forces may exceed planned retention.	Mechanical: Break	Failure of Operation Mode: Tension Release
	2	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage	STD	Sudden, Aging, Gradual	Relase before intended	Mechanical: Excess forces may exceed planned retention.	Mechanical: Break	Failure of Operation Mode: Tension Release
	3	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage	STD	Sudden, Aging, Gradual	Tension release mechanism fails to activate	Mechanical: Excess forces may exceed planned retention.	Mechanical: No Break	Partial loss of equipment (bottom sub and all equipment below)
	4	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	5	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage	STD	Sudden, Aging, Gradual	Lack of capacity to handle the hydraulic tension of tool string under retrieval	Mechanical: Excess forces may exceed planned retention.	Mechanical: Break	Partial loss of equipment (bottom sub and all equipment below)
	6	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Slotted Brass Flat-Tip Shear Screw - C675 Manganese Bronze	1	Mechanical	Mechanical: Break	Design Manufacturing Usage	2.5 Breakage	STD	Sudden, Aging, Gradual	Relase before intended	Mechanical: Excess forces may exceed planned retention.	Mechanical: Break	Partial loss of equipment
	2	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	3	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	4	Mechanical	Mechanical	Design Manufacturing Usage	2.5 Breakage	STD	Sudden, Aging, Gradual	The release of housing from bottom sub does not occur	Mechanical: Excess forces may exceed planned retention.	Mechanical: No Break	Loss of equipment
	5	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	6	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Torque Sub	1	Physical	Physical	Usage	1.1 Leakage	INL	Sudden, Aging, Gradual	Leak of hydraulic fluid	Lack of pressure	Insufficient amount of hydraulic fluid in resuar	Failure of Operation Mode: Tension Release
	2	Physical	Physical	Usage	1.1 Leakage	INL	Sudden, Aging, Gradual	Leak of hydraulic fluid	Lack of pressure	Insufficient amount of hydraulic fluid in resuar	Failure of Operation Mode: Tension Release
	3	Mechanical	Mechanical	Usage	1.3 Clearance / alignment failure 1.4 Deformation	STD OTH	Sudden	Teeth misaligned on impact	Mechanical: Deformed part may result in improper alignment	Mechanical - May result in tool displacement	Unable to perform function (shear) in a different operational mode
	4	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	5	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	6	Mechanical	Mechanical	Usage	2.5 Breakage	STD	Sudden, Aging, Gradual	Application of unexpected forces (mishandling) can lead to damage of the torque sub.	More costly and time consuming maintenance / repair	Longer lead times	Delayed operation between campaigns

Table 6 FMECA Safety

Safety				
Maintainable Item	**Operational Modes**	**Likelihood of Failure**	**Consequence of Failure**	**Risk Class**
Bottom Sub	Preparation: Installing in the String	2 - Low	B - Minor	1 - Pass
	Operation: Normal	1 - Negligible	D - Major	1 - Pass
	Operartion: Tension Release	2 - Low	D - Major	2 - Pass with Condition(2)
	Operation: Disconnecting	2 - Low	D - Major	2 - Pass with Condition(2)
	Retrieval: String from Well	Not relevant	Not relevant	Not relevant
	Transportation and Storage: Time between campaigns	4 - High	B - Minor	2 - Pass with Condition(2)
Mandrel	Preparation: Installing in the String	Not relevant	Not relevant	Not relevant
	Operation: Normal	1 - Negligible	C - Moderate	1 - Pass
	Operation: Tension Release	3 - Medium	D - Major	2 - Pass with Condition(2)
	Operation: Disconnecting	1 - Negligible	B - Minor	1 - Pass
	Retrieval: String from Well	1 - Negligible	B - Minor	1 - Pass
	Transportation and Storage: Time between campaigns	5 - Expected	B - Minor	3 - Fail
Compensating Piston	Preparation: Installing in the String	Not relevant	Not relevant	Not relevant
	Operation: Normal	2 - Low	B - Minor	1 - Pass
	Operation: Tension Release	4 - High	D - Major	3 - Fail
	Operation: Disconnecting	Not relevant	Not relevant	Not relevant
	Retrieval: String from Well	Not relevant	Not relevant	Not relevant
	Transportation and Storage: Time between campaigns	1 - Negligible	B - Minor	1 - Pass
Blank Shear Ring	Preparation: Installing in the String	1 - Negligible	B - Minor	1 - Pass
	Operation: Normal	5 - Expected	D - Major	3 - Fail
	Operartion: Tension Release	1 - Negligible	C - Moderate	1 - Pass
	Operation: Disconnecting	Not relevant	Not relevant	Not relevant
	Retrieval: String from Well	2 - Low	B - Minor	1 - Pass
	Transportation and Storage: Time between campaigns	Not relevant	Not relevant	Not relevant
Slotted Brass Flat-Tip Shear Screw - C675 Manganese Bronze	Preparation: Installing in the String	1 - Negligible	D - Major	1 - Pass
	Operation: Normal	Not relevant	Not relevant	Not relevant
	Operation: Tension Release	Not relevant	Not relevant	Not relevant
	Operation: Disconnecting	1 - Negligible	D - Major	1 - Pass
	Retrieval: String from Well	Not relevant	Not relevant	Not relevant
	Transportation and Storage: Time between campaigns	Not relevant	Not relevant	Not relevant
Torque Sub	Preparation: Installing in the String	1 - Negligible	B - Minor	1 - Pass
	Operation: Normal	1 - Negligible	D - Major	1 - Pass
	Operartion: Tension Release	5 - Expected	C - Moderate	3 - Fail
	Operation: Disconnecting	Not relevant	Not relevant	Not relevant
	Retrieval: String from Well	Not relevant	Not relevant	Not relevant
	Transportation and Storage: Time between campaigns	1 - Negligible	B - Minor	1 - Pass

Table 7 Criticality Analysis Safety

Security		Environmental Attack (Physical / Chemical / Thermal / Electrical / Process / Location)		Equipment Failure Profile (Design, manufacturing, usage (wear-out / aging))				Incidence	Operational Attack		Accident
Item	Mode	Environmental Threat	Environmental Attack Mechanism	Equipment Failure Cause	Equipment Failure Mechanism	Equipment Failure Mode	Equipment Failure Characteristics		Operational Hazard	Operational Attack Mechanism	
Bottom Sub	1	Chemical Mechanical	Chemical Mechanical	Design Usage	2.2 Corrosion 2.5 Breakage	FCO	Aging, Gradual	Tool restrictions limit mobility, reducing operational effectiveness and risking disconnection from lower well equipment, which could halt operations.	Mechanical Mechanical	Mechanical Mechanical	Tool restrictions limit mobility, reducing operational effectiveness and risking disconnection from lower well equipment, which could halt operations.
	2	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FTD	Sudden, Aging, Gradual	The tool strings fail to ascend from the well	Chemical Mechanical Thermal	Chemical Mechanical Thermal	The tool strings fail to ascend from the well
	3	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FTD	Sudden, Aging, Gradual	The tool strings fail to ascend from the well	Chemical Mechanical Thermal	Chemical Mechanical Thermal	The tool strings fail to ascend from the well
	4	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FTD	Sudden, Aging, Gradual	The tool strings fail to ascend from the well	Chemical Mechanical Thermal	Chemical Mechanical Thermal	The tool strings fail to ascend from the well
	5	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	6	Chemical Mechanical	Chemical Mechanical	Design Usage	2.2 Corrosion 2.5 Breakage	FCO	Sudden, Aging, Gradual	FCO: Failure to connect	Chemical Mechanical	Chemical Mechanical	Tool restrictions limit mobility, reducing operational effectiveness and risking disconnection from lower well equipment, which could halt operations.
Mandrel	1	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	2	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FCO	Sudden, Aging, Gradual	The connection fails and the pressure zones is not intact	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Failure of Operation Mode: Tension Release
	3	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FTD	Sudden, Aging, Gradual	The mandrel fail to slide out from housing	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Partial loss of equipment (bottom sub and all equipment below)
	4	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FCO	Sudden, Aging, Gradual	Loads over expected or design capacity resulting in breakage and cracking	Chemical Mechanical	Chemical Mechanical	Partial loss of equipment (bottom sub and all equipment below)
	5	Chemical Mechanical	Chemical Mechanical	Design Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FCO	Sudden, Aging, Gradual	Loads over expected or design capacity resulting in breakage and cracking	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Partial loss of equipment (bottom sub and all equipment below)
	6	Chemical Mechanical	Chemical Mechanical	Design Usage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	FCO	Sudden, Aging, Gradual	Integrity of the component is compromised for future use	More costly and time consuming maintenance / repair	Longer lead times	Delayed operation
Compensating Piston	1	Chemical Mechanical	Chemical Mechanical	Design Usage	1.1 Leakage	INL	Sudden, Aging, Gradual	A lack of hydraulic fluid	Mechanical	Mechanical	Not releasing at a later operational mode
	2	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	1.1 Leakage	INL	Sudden, Aging, Gradual	A lack of hydraulic fluid	Mechanical	Mechanical	Not releasing at a later operational mode
	3	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	1.1 Leaking 1.4 Deformation 2.2 Corrosion	INL STD	Sudden, Aging, Gradual	No tension release	Mechanical	Mechanical	Partial loss of equipment (bottom sub and all equipment below)
	4	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	5	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	6	Chemical Mechanical	Chemical Mechanical	Design Usage	2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Integrity of the component is compromised for future use	More costly and time consuming maintenance / repair	Longer lead times	Delayed operation
Blank Shear Ring	1	Chemical Mechanical	Chemical Mechanical	Design Usage	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Relase before intended	Mechanical	Mechanical	Partial loss of equipment (bottom sub and all equipment below)
	2	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Relase before intended	Mechanical	Mechanical	Partial loss of equipment (bottom sub and all equipment below)
	3	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Tension release mechanism fails to activate	Mechanical	Mechanical	Partial loss of equipment (bottom sub and all equipment below)
	4	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	5	Chemical Mechanical	Chemical Mechanical	Design Usage	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Lack of capacity to handle the hydralic tension of tool string under retrieval	Mechanical	Mechanical	Retrieval of a tool causing unintended tension release
	6	Chemical Mechanical	Chemical Mechanical	Design Usage	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Integrity of the component is compromised for future use	More costly and time consuming maintenance / repair	Longer lead times	Delayed operation
M10 x 1.5 x 12 Slotted Brass Flat-Tip Shear Screw - C675 Manganese Bronze	1	Chemical Mechanical	Chemical Mechanical	Design Usage	1.3 Clearance/alignment failure 1.5 Looseness 2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Looseness	Mechanical	Mechanical	Equipment located beneath the BSPJ is lost, requiring the removal of the string
	2	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	1.3 Clearance/alignment failure 1.5 Looseness 2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Looseness	Mechanical	Mechanical	Equipment located beneath the BSPJ is lost, requiring the removal of the string
	3	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	1.3 Clearance/alignment failure 1.5 Looseness 2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Looseness	Mechanical	Mechanical	Equipment located beneath the BSPJ is lost, requiring the removal of the string
	4	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	5.3 Miscellaneous external influences	FTF	Sudden, Aging, Gradual	Signal failure	Mechanical	Mechanical	Retrieval failed and complete loss of string equipment
	5	Chemical Mechanical	Chemical Mechanical	Design Usage	1.3 Clearance/alignment failure 1.5 Looseness 2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Looseness	Mechanical	Mechanical	Loss of equipment below BPSJ
	6	Chemical Mechanical	Chemical Mechanical	Design Usage	2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Integrity of the component is compromised for future use	More costly and time consuming maintenance /	Longer lead times	Delayed operation
Torque Sub	1	Chemical Mechanical	Chemical Mechanical	Design Usage	1.1 Leakage	INL	Sudden, Aging, Gradual	Leak of hydraulic fluid	Mechanical	Mechanical	Not releasing at a later operational mode
	2	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	1.1 Leakage	INL	Sudden, Aging, Gradual	Leak of hydraulic fluid	Mechanical	Mechanical	Not releasing at a later operational mode
	3	Chemical Mechanical Thermal	Chemical Mechanical Thermal	Design Usage	1.4 Deformation	STD	Sudden, Aging, Gradual	Weaking of the structural component	Mechanical	Mechanical	Not releasing at a later operational mode
	4	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	5	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	6	Not relevant	Not relevant	Design Usage	2.2 Corrosion 2.5 Breakage	STD	Sudden, Aging, Gradual	Integrity of the component is compromised for future use	More costly and time consuming maintenance / repair	Longer lead times	Delayed operation

Table 8 FMECA Security

Security				
Maintainable Item	**Operational Modes**	**Likelihood of Failure**	**Consequence of Failure**	**Risk Class**
Bottom Sub	Preparation: Installing in the String	3 - Medium	A - Slight	1 - Pass
	Operation: Normal	1 - Negligible	E - Massive	2 - Pass with Condition(2)
	Operartion: Tension Release	1 - Negligible	E - Massive	2 - Pass with Condition(2)
	Operation: Disconnecting	1 - Negligible	E - Massive	2 - Pass with Condition(2)
	Retrieval: String from Well	Not relevant	Not relevant	Not relevant
	Transportation and Storage: Time between campaigns	1 - Negligible	C - Moderate	1 - Pass
Mandrel	Preparation: Installing in the String	Not relevant	Not relevant	Not relevant
	Operation: Normal	1 - Negligible	C - Moderate	1 - Pass
	Operation: Tension Release	1 - Negligible	D - Major	1 - Pass
	Operation: Disconnecting	1 - Negligible	C - Moderate	1 - Pass
	Retrieval: String from Well	1 - Negligible	C - Moderate	1 - Pass
	Transportation and Storage: Time between campaigns	5 - Expected	C - Moderate	3 - Fail
Compensating Piston	Preparation: Installing in the String	1 - Negligible	C - Moderate	1 - Pass
	Operation: Normal	1 - Negligible	C - Moderate	1 - Pass
	Operation: Tension Release	1 - Negligible	D - Major	1 - Pass
	Operation: Disconnecting	Not relevant	Not relevant	Not relevant
	Retrieval: String from Well	Not relevant	Not relevant	Not relevant
	Transportation and Storage: Time between campaigns	2 - Low	D - Major	2 - Pass with Condition(2)
Blank Shear Ring	Preparation: Installing in the String	1 - Negligible	C - Moderate	1 - Pass
	Operation: Normal	1 - Negligible	C - Moderate	1 - Pass
	Operartion: Tension Release	1 - Negligible	C - Moderate	1 - Pass
	Operation: Disconnecting	Not relevant	Not relevant	Not relevant
	Retrieval: String from Well	1 - Negligible	E - Massive	2 - Pass with Condition(2)
	Transportation and Storage: Time between campaigns	1 - Negligible	C - Moderate	1 - Pass
Slotted Brass Flat-Tip Shear Screw - C675 Manganese Bronze	Preparation: Installing in the String	1 - Negligible	C - Moderate	1 - Pass
	Operation: Normal	1 - Negligible	C - Moderate	1 - Pass
	Operation: Tension Release	1 - Negligible	C - Moderate	1 - Pass
	Operation: Disconnecting	1 - Negligible	C - Moderate	1 - Pass
	Retrieval: String from Well	1 - Negligible	C - Moderate	1 - Pass
	Transportation and Storage: Time between campaigns	1 - Negligible	C - Moderate	1 - Pass
Torque Sub	Preparation: Installing in the String	1 - Negligible	D - Major	1 - Pass
	Operation: Normal	1 - Negligible	D - Major	1 - Pass
	Operartion: Tension Release	3 - Medium	A - Slight	1 - Pass
	Operation: Disconnecting	Not relevant	Not relevant	Not relevant
	Retrieval: String from Well	Not relevant	Not relevant	Not relevant
	Transportation and Storage: Time	1 - Negligible	A - Slight	1 - Pass

Table 9 Criticality Analysis Security

Step 7: Selection of Maintenance Actions

The maintenance actions recommended were determined by referencing Table B.5 in ISO 14224:2016, which provided action codes such as 9 (inspection), 3 (modify), and 5 (refit). This standardized framework ensured that the maintenance activities aligned with industry best practices. Additionally, Entech provided the team with a PM manual on downhole tools, which was utilized in implementing the recommended maintenance actions. Maintenance actions were advised for items that received a risk classification of 2-Pass with condition(s)" and 3-Fail.

Safety		Criticality Analysis	
Item	Mode	Risk Class	Risk Management Measures
Bottom Sub	3	2 - Pass with Condition(s)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Inspect for damage every time the tool is run in the wellbore, disassmbled, transported, or handled. * Clean and inspect all sealing surfaces for minor pits and scratches. If pits and scratches are visible, remove with an emery cloth. * Clean and inspect threaded surfaces for damage such as deformation, stripping, or burrs. * Ensure the correct size o-rings and backup rings.
	4	2 - Pass with Condition(s)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Inspect for damage every time the tool is run in the wellbore, disassmbled, transported, or handled. * Clean and inspect all sealing surfaces for minor pits and scratches. If pits and scratches are visible, remove with an emery cloth. * Clean and inspect threaded surfaces for damage such as deformation, stripping, or burrs. * Ensure the correct size o-rings and backup rings.
	6	2 - Pass with Condition(s)	9. Inspection * Inspect for damage every time the tool is run in the wellbore, disassmbled, transported, or handled. * Clean and inspect all sealing surfaces for minor pits and scratches. If pits and scratches are visible, remove with an emery cloth. * Clean and inspect threaded surfaces for damage such as deformation, stripping, or burrs. * Ensure the correct size o-rings and backup rings.
Mandrel	3	2 - Pass with Condition(s)	9. Inspection * Inspect for damage every time the tool is run in the wellbore, disassmbled, transported, or handled. * Clean and inspect all sealing surfaces for minor pits and scratches. If pits and scratches are visible, remove with an emery cloth. * Clean and inspect threaded surfaces for damage such as deformation, stripping, or burrs. * Ensure the correct size o-rings and backup rings.
	6	3 - Fail	9. Inspection * Inspect for damage every time the tool is run in the wellbore, disassmbled, transported, or handled. * Clean and inspect all sealing surfaces for minor pits and scratches. If pits and scratches are visible, remove with an emery cloth. * Clean and inspect threaded surfaces for damage such as deformation, stripping, or burrs. * Ensure the correct size o-rings and backup rings. 3. Modify * Apply new coating and corrosion inhibitor
Compensating Piston	3	3 - Fail	3. Modify * Re-design the teeth on the component to withstand deformation during impact. * Add security measures that prevent the component from becoming misaligned.
Blank Shear Ring	2	3 - Fail	3. Modify * Re-design the bearing ring to better support the shear ring, and/or larger set-point for shear force, and/or manage shock loads during perforating.
Torque Sub	3	3 - Fail	3. Modify * Re-design the teeth on the component to withstand deformation during impact. * Add security measures that prevent the component from becoming misaligned.

Table 10 Maintenance Actions - Safety

Security ⍰		Criticality Analysis	
Item	Mode	Risk Class	Recommended actions(s)
Bottom Sub	2	2 - Pass with Condition(s)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Close visual inspection of the threads for damages such as deformation, stripping, or burrs. * Disassemble, inspect, and deep clean the component. * Remove contaminants and residual wellbore fluid. * Thoroughly dry componet and apply a corrosion inhibitor. * Outside storing: fully assembled with all seals and thread protectors. * Do not store on the ground. * Store in climate controlled environment or outside under a cover submerged in 0-ring friendly corrosion inhibitor fluid.
	3	2 - Pass with Condition(s)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Close visual inspection of the threads for damages such as deformation, stripping, or burrs. * Disassemble, inspect, and deep clean the component. * Remove contaminants and residual wellbore fluid. * Thoroughly dry componet and apply a corrosion inhibitor. * Outside storing: fully assembled with all seals and thread protectors. * Do not store on the ground. * Store in climate controlled environment or outside under a cover submerged in 0-ring friendly corrosion inhibitor fluid.
	4	2 - Pass with Condition(s)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Close visual inspection of the threads for damages such as deformation, stripping, or burrs. * Disassemble, inspect, and deep clean the component. * Remove contaminants and residual wellbore fluid. * Thoroughly dry componet and apply a corrosion inhibitor. * Outside storing: fully assembled with all seals and thread protectors. * Do not store on the ground. * Store in climate controlled environment or outside under a cover submerged in 0-ring friendly corrosion inhibitor fluid.
Mandrel	6	3 - Fail	9. Inspection * Disassemble, inspect, and deep clean each component. * Remove contaminants and residual wellbore fluid. * Thoroughly dry componet and apply a corrosion inhibitor. * Outside storing: fully assembled with all seals and thread protectors. * Do not store on the ground. * Store in climate controlled environment or outside under a cover submerged in 0-ring friendly corrosion inhibitor fluid.
Compensating Piston	6	2 - Pass with Condition(s)	5. Refit Rinse surface before transportation and storage
Blank Shear Ring	5	2 - Pass with Condition(s)	9. Inspection Close visual inspection of the shear ring to detect mechanical weakness and/or corrosion.

Table 11 Maintenance Actions - Security

Step 8: Determination of Maintenance Intervals

Determination of maintenance intervals will not be assessed as the BPSJ cannot undergo inspection maintenance whilst in operation, as the tool will be inaccessible to maintenance operators. Therefore, inspection maintenance activities can only be completed during certain operational modes, such as, *before* operational mode (1) Preparation: Installing in the string and *after* retrieval of the string before operational mode (6) Transportation and Storage: Time between campaigns. In the previous RCM step, if in any operational mode where the BPSJ is in operation, but an item was classified as “pass with condition(s)” or “fail”, the recommended maintenance activities are to take place between campaign.

Step 12: In-service Data Collection and Updating

As operational data becomes available for the BPSJ, a record of the maintenance program should be documented. Such as what issues were encountered, cause of the issue, and how it was resolved. This type of identification and documentation allows the operators in charge of maintenance to identify recurring issues, assess their criticality, and prioritize the maintenance activities accordingly.

The collection of data and the continuous updating of records as new data becomes available can improve various RCM analysis steps with respect to time. These improvements include enhancing the RCM medium-term task evaluation steps such as step 6 (FMECA) and step 7 (selection of maintenance actions) by identifying failure modes that were previously overlooked, updating the criticality analysis of existing failure modes, and determining the effectiveness of maintenance actions. This, in turn, enables adjustments to the maintenance plan to optimize maintenance activities.

4.3 Quality Alert Rapport

Approximately a month after commencing the project, the first report regarding the equipment's performance during a campaign was published. The report, provided in appendix D, highlighted the deficiencies that require further investigation. Cause-and-effect analysis will be used for the investigation. In addition, the team conducted a separate analysis of a specific component that had experienced a functional failure. By investigating these components, the team hoped to gain a better understanding of its performance and identify any potential issues that could impact the sub-system's overall functionality.

4.3.1 Deficiency 1 – Shear ring

When the tool was retrieved from the well after use, it was discovered that the Tension Release had been activated unintentionally and that the BPSJ was stroked open. As described earlier in the chapter, Tension Release is activated by a shear ring. Given that the mechanism in question can only be employed once, the ring not shearing when intended would defeat the purpose of the tool. Tension Release will then fail to be readily available for use when the need arises, further emphasizing the importance of its proper functionality. A further result of post-shearing is that wellbore fluids will flow into the tool, which may cause corrosion damage to other components. It is imperative to conduct a cause-and-effect analysis to comprehensively understand the underlying factors that have contributed to the issue at hand.

Cause-and-effect analysis - Deficiency 1

The diagram presented below illustrates the outcomes of a cause-and-effect analysis that was performed to identify the root causes and effects of Deficiency 1.

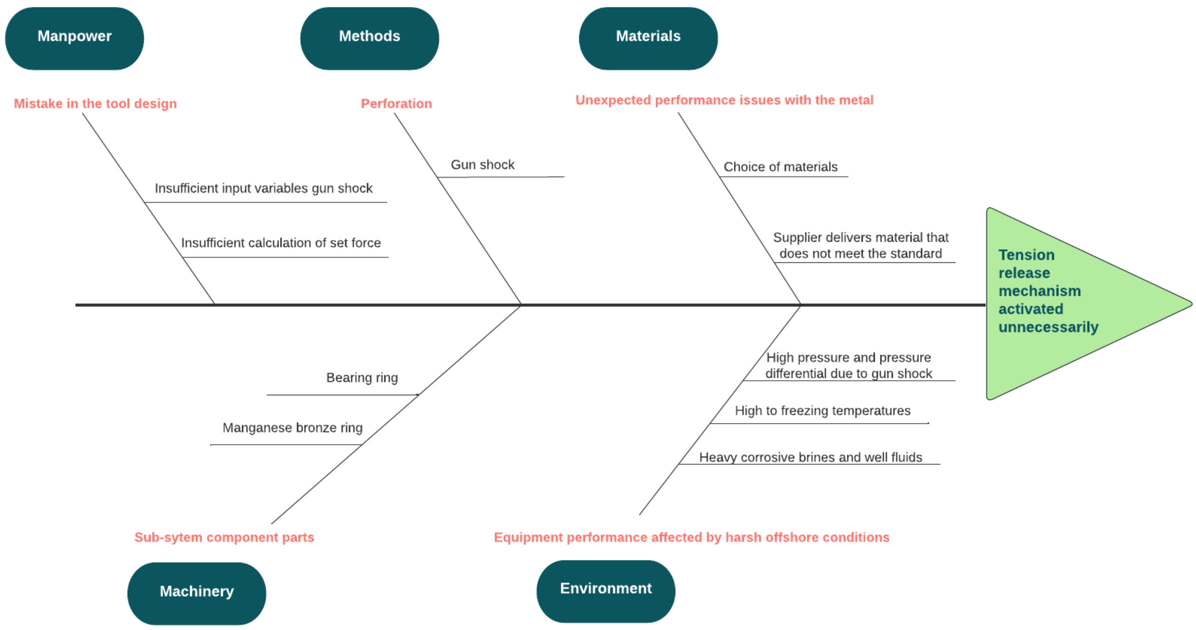


Figure 27 Fishbone Analysis - Deficiency 1

Fishbone analysis incorporates perforation and the resultant forces exerted on the tool from gun impact, is entered into the methods category, identifying them as potential contributing factor for failure. A possible cause is that the tool is being subjected to a sudden and significant increase in axial load and weight due to the impact of the gun shock. The effect of the gunshot on the shear ring at the time of firing is enough force to break the shear ring, causing the BPSJ to stroke open. [10] Potential solutions for deficiency 1 will be discussed with this cause as the basis for function failure.

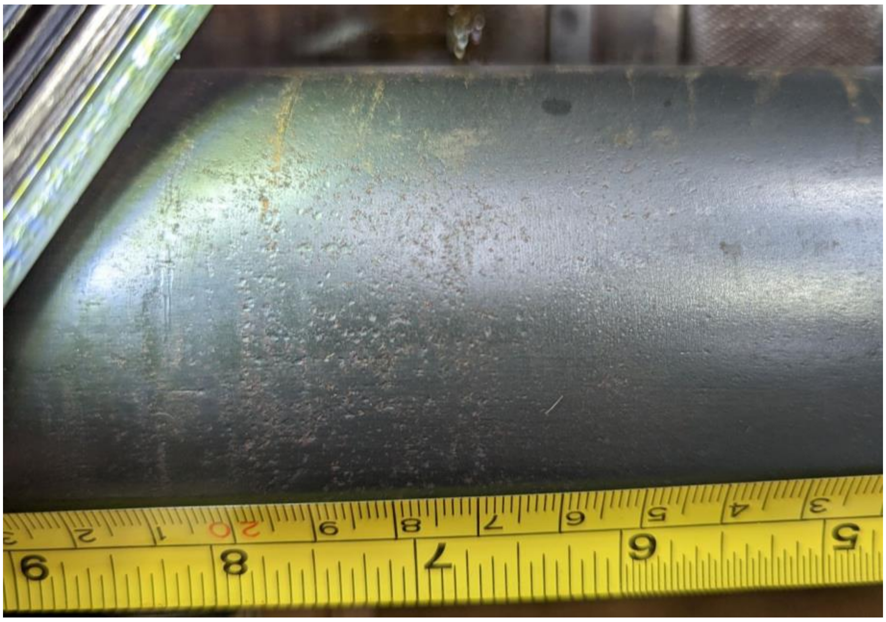
The team discussed with Entech and their customer various solutions to prevent the early shearing of the shear ring. One potential solution was to increase the shearing value of the ring. A discussion assessing if increasing the surface area of the contact area between Blank Shear Ring and Bearing Ring. Dispersing the forces across a larger area could be a possible solution. Which could possibly alleviate the effect of the gun shock on the shear ring. An excessive increase in such value may result in the ring not shearing when intended which would defeat the purpose of the tool. Therefore, there needs to be a balance between having the ring respond as intended and not shearing unnecessarily.

Another possible solution was to redesign the tension ring or other components within the tool to create an initial absorption effect. There were discussions surrounding the possibility of incorporating a shock absorber, cushion or honeycomb design, or another elastic material to create some kind of dampening effect to reduce the number of scenarios where early shear takes place. However, there needs to be enough room in the tool to implement this solution.

Additionally, it’s difficult to find a solution that completely eliminates the problem, because there are many dynamic effects in the well that cause shock waves to hit the tool in tension. Nonetheless, by introducing a dampening mechanism, it is possible to vastly reduce the occurrence of early shear. Although this may not entirely solve the problem, it is a significant improvement in preventing the early shearing of the shear ring, which will prolong the life of the tool and minimize damage to other components.

4.3.2 Deficiency 2 – Corrosion

One of the main deficiencies identified during the quality alert report was the development of pitting on the Mandrel seal surface. At this given moment the pitting does not affect tool ratings or specifications. One of the challenges with pitting corrosion is that it can be difficult to detect and monitor, as it often occurs beneath the surface of the material. This issue not only poses a risk to the equipment's integrity but can also negatively impact its performance, potentially leading to unplanned downtime and costly repairs. As such, it is imperative that measures be taken to address this issue and carry out a Cause-and-effect analysis. .



Picture 1 Pitting on Mandrel

Cause-and-effect analysis - Deficiency 2

The diagram presented below illustrates the outcomes of a cause-and-effect analysis that was performed to identify the root causes and effects of Deficiency 2

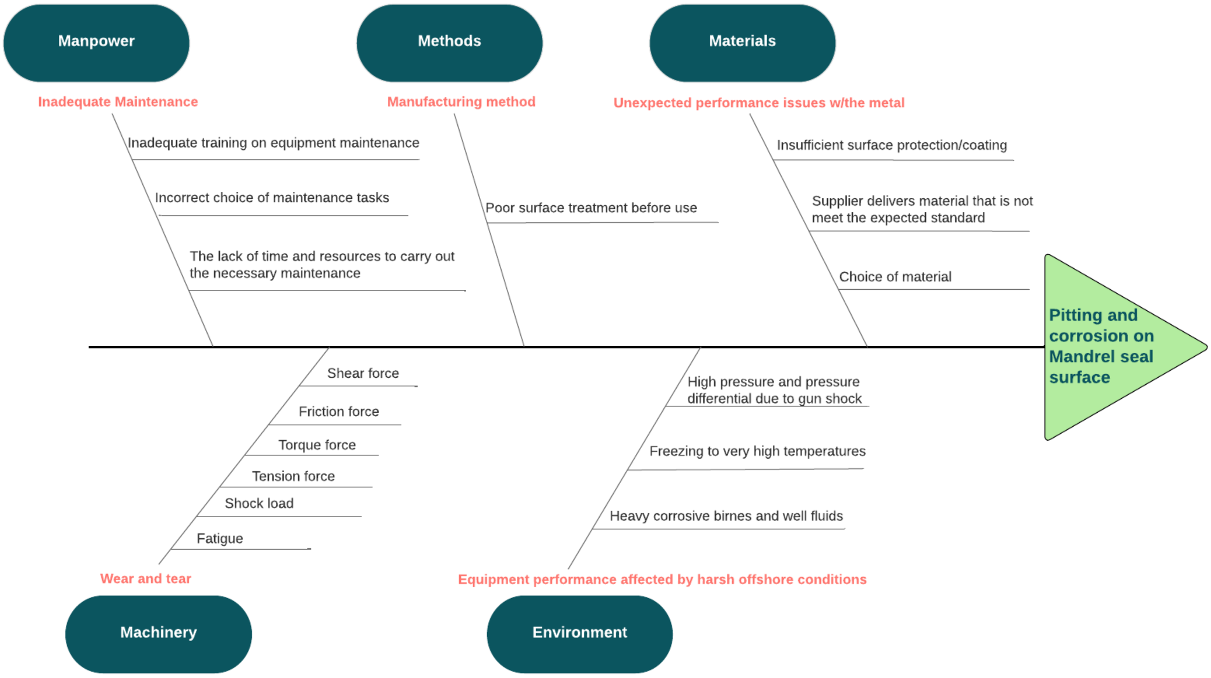


Figure 28 Fishbone diagram - Deficiency 2

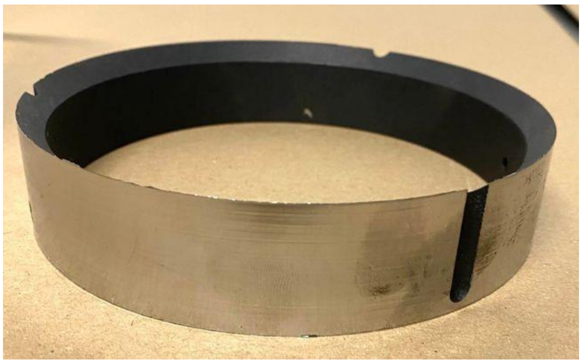
The fishbone analysis hypothesized that pitting occurs not due to liquid submersion, but rather after retrieval from the well when the tool is exposed to oxygen. Specifically, the BPSJ sometimes sits on a platform for multiple days after retrieval without being rinsed with fresh water. The tool may then spend an additional two days on a boat whilst heading back to land, during which time it will be rinsed with seawater but then left to sit on the shore in the sun for a couple more days, before being returned to the operations base for maintenance. These conditions are believed to promote the corrosion and pitting of the BPSJ's surface, which can compromise its performance and longevity. [10] Furthermore, this hypothesis will be investigated with Corrosion testing.

Corrosion Test

To find a suitable solution for deficiency 2 a laboratory experiment was initiated to test the hypothesis discussed in the Fishbone analysis. Through laboratory experiments the team aims to provide an understanding of the factors that contribute to pitting. An understanding of the factors will give the team the opportunity to propose potential solutions for mitigating its occurrence.

It's important to understand the factors that need to be present for corrosion to take place. There are three conditions that are necessary, such as: "1. Metal, 2. Water or electrolyte, 3. A corrodent". [20] In the field the Mandrel is exposed to seawater and well fluid as an electrolyte. In the test only well fluid was experimented with, oxygen as a corrodent and the metal AISI 4140 was the same for both scenarios. Based on the factors surrounding the tool and the tool itself, all three of the necessary conditions for corrosion to take place are present, especially after retrieval.

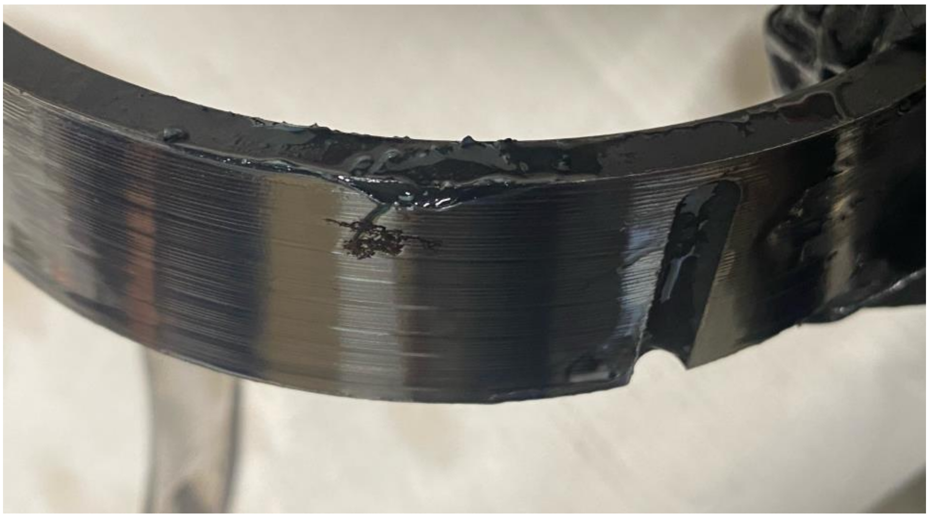
For the test, three metal rings samples were chosen. The sample was made of the same metal as the Mandrel, AISI 4140. The inside was coated with manganese phosphate and the outside was machined with no surface treatment. Three samples of well fluid were transported from customers and used in testing. The three well fluids were Potassium Chloride (KCL brine), Calcium Chloride ($CaCl2$ brine), Calcium Bromide ($CaBr2$ brine). This will simulate the environmental threat the mandrel is exposed to in the operation process.



Picture 2 Test Sample

Corrosion testing was completed to assess which part of the operations process is the biggest threat to the tool. To simulate the tool in operation process when installed in string, each of the samples were submerged in three different wellbore fluid for 22 days. After the first test period a visual inspection was done. To continue the testing the bin was turned on their side, so the top half part of the ring would no longer lay submerged in the fluid but rather become exposed to oxygen in the bin. This was done to simulate the retrieval of the string. After two more weeks the rings were again inspected for corrosion, and the laboratory experiment was concluded.

There were two inspections of the samples during the testing period. In the first inspection there was observed discoloration on the outside of the test sample as well as in the fluid. An unknown black liquid was discovered in one of the test samples.



Picture 3 From fluid 3

At the next inspection, it was observed an increase in corrosion on the top part of the samples that were exposed to oxygen. The part of the ring that remained submerged in the well fluid the entire length of experiment did not have the same increase in corrosion.

In conclusion, the team's observations during the experiment revealed a significant increase in the rate of corrosion once the metal rings were exposed to oxygen. These findings support the team's initial hypothesis that the biggest threat to the tool is not during operation, but rather after retrieval and during transportation. As it is unavoidable that the tool will be exposed to oxygen once it is retrieved, further measures should be taken to thoroughly rinse the tool as soon as possible, as well as keep the tool out of the sun. Besides this, a coating can be applied to protect the tool to increase the longevity and effectiveness of the tool.

Picture 4 Corrosion Test

Coating Analysis

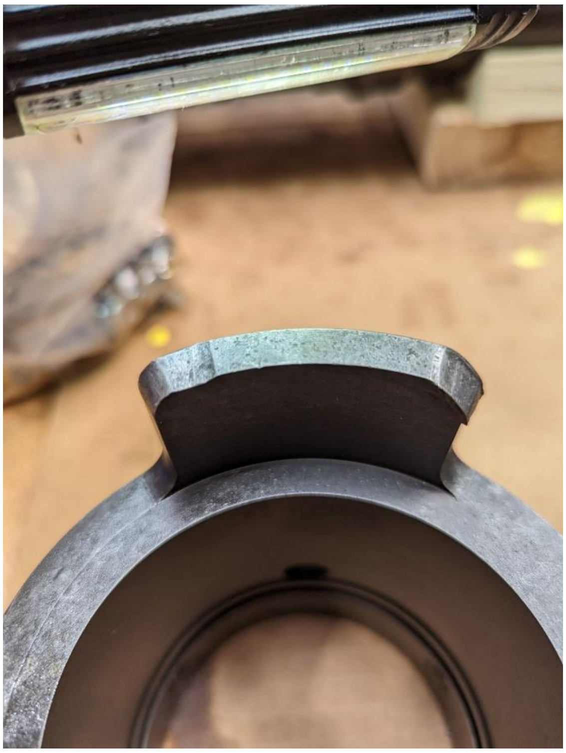
Once it was determined that the tool was highly vulnerable to corrosion, efforts were made to find a suitable new surface treatment. This involved researching various coating options from a company in Houston, Texas, which had a diverse range of coatings in its portfolio.

A comprehensive assessment was conducted to identify the different environmental conditions the tool could face. Conditions that may affect corrosion in the well are temperature variations, CO2, hydrocarbon exposure, mud, hydrochloric acid, and saltwater containing chemicals like calcium bromide. Additionally, brines with a low pH are highly corrosive. After analyzing these factors, different types of coatings were evaluated including electroless nickel, SBN-QPQ (salt bath nitrite), spray coatings like epoxy and molybdenum disulfide. The protective coating will help to prevent corrosion and enhance the tool's durability.

The QPQ coating is recommended for the tool due to its superior properties compared to the current coating. It is harder, more durable, and offers better corrosion resistance. By using this surface treatment, it is possible to protect the seal surface and potentially extend the useful lifespan of the mandrel.

4.3.3 Deficiency 3 – Deformation

The equipment analysis has revealed another major deficiency, it was discovered deformation on the "ears", or the lug/teeth of the Compensating Piston and Torque Sub. The deformation had occurred at the point of contact, on the edge of the teeth. This can have significant consequences, including decreased operational efficiency and potential equipment failure such as the inability to transfer torque. This can result in unplanned downtime, costly repairs, and worst-case scenario-loss of equipment. Addressing this issue is vital, as it could help prevent major equipment failure and ensure that the equipment functions optimally for the duration of its lifespan. Further investigation measures are to be performed by a Cause-and-effect analysis.



Picture 6 Top view - Deformation teeth

Picture 5 Side view - Deformation teeth

Cause-and-effect analysis – Deficiency 3

The following diagram depicts the results of a cause-and-effect analysis conducted to identify the causes and effects of Deficiency 3.

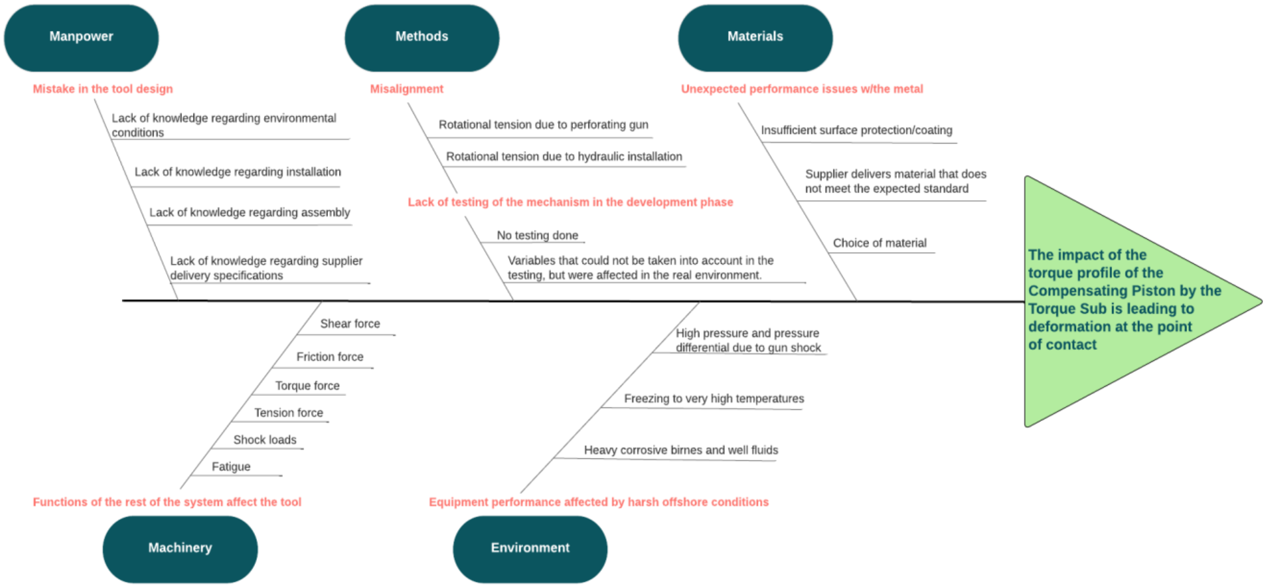


Figure 29 Figure 15: Fishbone diagram for deficiency 3

In the Fishbone analysis misalignment is identified as a potential contributing factor for the deformation. After analyzing the issue, the team determined that during tool compression, the compensating piston and torque were failing to align correctly and were colliding with each other, resulting in flaring. The misalignment may be a result of rotational tension created from descending the tool string into the well. The tension is held by the teeth of the bottom sub and torque sub. When the tension release is activated, the teeth will disengage, and the mandrel will rotate slightly.

During a collective meeting with Entech and their customer potential solutions of deformation was discussed. The discussion involved a possible design change surrounding the teeth as the most optimal solution. Solutions include increasing the number of teeth to reduce point loading and/or implementing an angle force transfer profile with more contact area to distribute the force over multiple points. In order to determine the optimal solution, further testing of redesigned items is necessary to prevent future failures.

5. Discussion and Results

In this section, we will provide an interpretation of the results presented in the case study, and discuss their implications, as well as potential for future research.

5.1 RCM Results

To begin the study, a technical hierarchy was established for the BPSJ sub-system by breaking it down into its maintainable items, as detailed in Chapter 4, Step 3. A Functional Failure Analysis (FFA) was then conducted to examine how the sub-system functions and how it interacts with its surroundings. The potential risks associated with each item were also evaluated to identify potential functional failures. The items that were identified as critical in terms of functional failures were selected for further analysis, specifically those that were considered Maintenance Significant Items (MSIs). This approach ensured that resources were focused on analyzing components that posed a significant risk rather than on those that were deemed less critical. Ultimately, the team identified six items that were considered MSIs, including the bottom sub, compensating piston, shear screw, mandrel, blank shear ring, and torque sub.

The team completed a Failure Modes, Effects, and Criticality Analysis (FMECA) to assess the likelihood and consequence of failure for each item, as outlined in appendix F.4-F.15. The analysis resulted in a Criticality Analysis that classified each item. Most of the items were classified as 1-Pass, indicating that they posed a low risk of failure. However, those components that were determined to be 2-Pass with Condition(s) or 3-Fail were recommended for specific maintenance actions, which are listed in the table in Chapter 4, Step 7. In addition, the mandrel, blank shear ring, compensating piston, and torque sub were classified as 3-Fail, prompting a Cause-and-effect analysis to identify potential solutions to prevent such failures.

Through the analysis, the team identified that the shear ring was inadvertently shearing, causing issues not only by being released unnecessarily, but also causing problems for other components, such as corrosion on the mandrel and deformation on the compensating piston and torque sub. While the deformation was not directly caused by the shear ring, it was observed that the deformation was occurring at the point of contact when the shear ring was shearing off too early. To address this issue, a solution needs to be implemented to prevent inadvertent shearing. Furthermore, a design change needs to be implemented to prevent deformation at the point of contact of the compensating piston and torque sub.

Finally, to minimize corrosion on the tool in general, surface protection needs to be implemented as soon as possible. The study provides a detailed discussion of these quality issues in Chapter 4.3. A corrosion test was also conducted to determine which part of the operational process is causing corrosion on the BPSJ. The test revealed it was likely the rate of corrosion was significantly increased when the tool was out of the well and exposed to oxygen without being rinsed with fresh water and left exposed to the sun. Therefore, maintenance procedures need to be implemented as soon as the tool comes out of the well in the form of rinsing as well as investing in a protective surface layer to prevent metal corrosion.

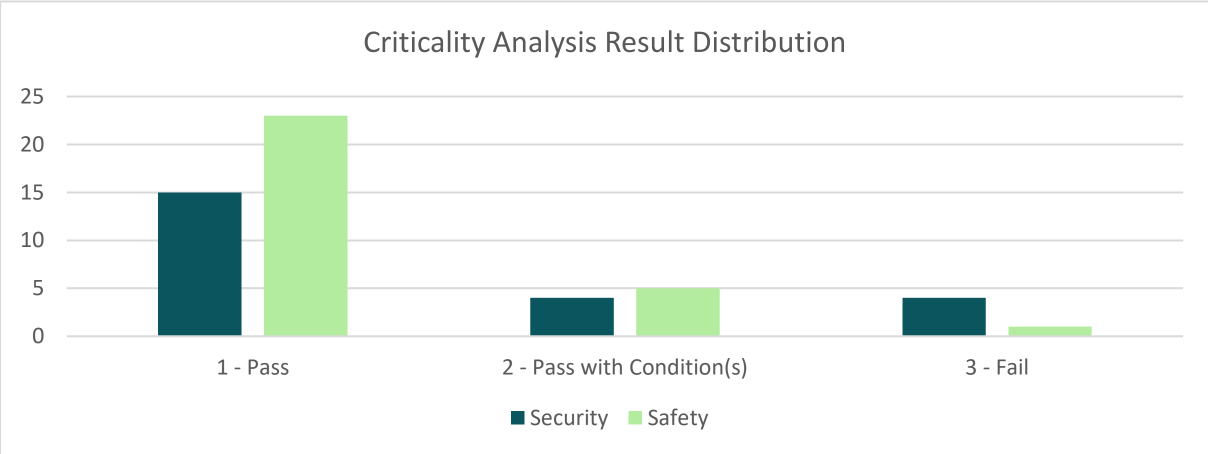


Table 12 Criticality Result

According to the analysis, the observed failures are deemed to be a normal occurrence expected during the initial phase of the bathtub curve. The bathtub curve is a widely used tool in reliability engineering for assessing the behavior of products and systems over their lifespan. It is anticipated that the number of failures will decrease in the future, as it moves beyond the initial phase of the bathtub curve. The now lower failure rate is expected to be caused by aging, wear, and tear of components or materials.

5.2 Cause-and-effect analysis

Blank Shear Ring got classified 3–Fail in the safety analysis, with the accident “Release before intended”. After use, the tool was found with unintentionally activated Tension Release and an open BPSJ, potentially causing corrosion damage. Fishbone analysis suggests gun impacts may have caused a sudden increase in load, breaking the shear ring. To solve this, the team discussed two potential solutions: increasing the shearing value of the ring and redesigning the tool to absorb shock. A balance must be struck to avoid defeating the purpose of the tool. Dampening mechanisms may not completely solve the problem, but they can significantly reduce early shearing and prolong tool life.

The Mandrel got classified 3–Fail in the security analysis, with the incidence “Integrity of the component is compromised for future use”. Pitting was found on the Mandrel seal surface, which can negatively affect equipment performance and integrity. The cause is believed to be exposure to oxygen after retrieval from the well, without rinsing with fresh water. Corrosion testing was done to conclude the investigation.

Compensating piston and torque sub got the classified 3–Fail in the safety analysis, with the accident "Teeth misaligned on impact". Misalignment was identified as a potential factor for deformation in Fishbone analysis. The team found that the compensating piston and torque sub were colliding during tool compression due to a rotational tension created during tool string descent. The team, Entech and their customer discussed design changes to address the issue, including increasing the number of teeth or implementing an angle force transfer profile for better force distribution.

5.3 Challenges and Limitations

During the execution of the project, several challenges and limitations were encountered, which impacted both scope and execution. One of the significant challenges was the geographical location of the tool, which made it impossible for the team to access and inspect it in person. As a result, the team did not communicate to maintenance operators who oversee and perform maintenance on the tool between campaigns. Resulting in a lack of valuable information that could have been gathered and analyzed.

One of the major challenges in performing an RCM analysis was the collaboration required among several people across different time zones. The challenge in obtaining information originates from meeting limitations, correspondence through e-mail and general knowledge exchange. Causing delays or temporary uncertainty during the analysis. Additionally, due to time restrictions the team was unable to complete additional testing on further steel samples.

The novelty of the tool posed a limitation since there was a lack of historical reliability data, and maintenance routines to build the analysis around. Although the research was built on the expertise of the tool designers and users, the study was still constrained by the lack of comprehensive statistical analysis. Consequently, the accuracy and reliability of the maintenance tasks developed in the study are limited.

Furthermore, human error was taken into limited account, given the tools passive nature as it's self-sufficient whilst in operation. There are only a few operational modes where human error could cause the failure of the tool, which with time would need further consideration. Additionally, the current inspection- and maintenance plan is limited, which meant that the FMECA analysis had to be completed almost from the ground up. Entech's general PM for downhole tools was implemented into the team's FMECA as a starting point. However, further research and development would be necessary to create a more effective plan going forward.

The RCM analysis process is a challenging one, requiring the team to break down and analyze each component's function. The process requires strong analytical skills and teamwork to complete a thorough analysis. Resulting in each component receiving a criticality ranking. This ranking includes how it may fail, as well as the likelihood, and consequences of its failure. Ranking each component's criticality is a particularly challenging decision, as it is purely based on a subjective opinion.

Additionally, incorporating cybersecurity concepts into a mechanical system, required a lot of effort which was time-consuming. It involved analyzing and understanding safety and security aspects and how they could be complementary, making for a more comprehensive analysis. It was challenging to reconcile technical terms from diverse fields, which required additional effort to bridge these knowledge gaps and ensure that everyone involved in the project was on the same page, which added to the overall complexity of the process.

5.4 Recommendations Going Forward

The RCM for this project was started after the tool was already in use. For future work it is recommended to incorporate RCM during the development phase. It should be integrated as early as the concept or design phase to assist in the selection of a design that fulfils the safety, security, and reliability potential. Integrating an RCM analysis during the implementation of any design, one can proactively anticipate potential outcomes and make informed decisions. This foresight makes it possible to identify and address any issues before they escalate, ensuring a more robust and reliable system overall.

The RCM ability to incorporate maintenance experience feedback into the analysis process provides a comprehensive and effective maintenance strategy. Therefore, it’s strongly recommended to continuously update the process, based on short-term, medium-term, and long-term time perspectives. As operational data becomes available, a record of the maintenance program should be documented to identify failures, especially repetitive failures. The collection of data and continuous updating of records can improve various RCM analysis steps, allowing adjustments to the maintenance and to optimize maintenance activities.

6. Conclusion

RCM improves a system's reliability and reduces the risk of failure. The essential part of starting an RCM is the study of the sub-system in question, its functions, and its various components. From the Study Preparation system definitions were established, different functions, different interfaces, and the functional failures. After this groundwork was completed, the Critical Item Selection and FMECA was implemented, and maintenance actions were recommended.

There is a strong belief that the maintenance actions that were selected will increase the life span of the tool, thereby making it a cost-effective intervention. Despite its effectiveness, it is important to acknowledge that RCM is not flawless and may potentially overlook functional failures, failure modes, or other contributing factors. The absence of accurate and reliable data presented a challenge in performing a quantitative analysis, thereby necessitating alternative methods to be employed. Hence, it is recommended to periodically review and update the RCM analysis to ensure its continued relevance and effectiveness and maintain detailed records of maintenance activities. It is also suggested to incorporate RCM during the design phase of a project to anticipate potential issues and ensure a more robust and reliable system.

Based on a subjective approach an FMECA was established which led to a study of root cause. Root cause analysis was completed on the four critical items that failed. A selection of solutions was proposed to address the failed components. Solutions as coating, redesign, inspection and cleaning the tool after use were discussed and recommended. It is appreciated that Entech will take these recommendations seriously and actively pursue the further development and refinement of the RCM process.

7. References

[1] "Risk management - Guidelines," NS-ISO 31000:2018.

[2] "Criticality analysis for maintenance purposes," Z-008; 2001.

[3] "Maintenance - Maintenance terminology," BS EN 13306: 2010.

[4] "Petroleum, petrochemical and natural gas industries — Collection and exchange of reliability and maintenance data for equipment," ISO14224; 2016(E).

[5] M. Rausand, System Reliability Theory Models, Statistical Methods, and Applications, Wiley, 2004.

[6] "Asset management — Overview, principles and terminology," ISO 55000:2014.

[7] "Systems and software engineering — System life cycle processes," ISO/IEC/IEEE 15288:2015.

[8] D. Firesmith, "Common Concepts Underlying Safety, Security, and Survivability Engineering," Carnegie Mellon University, 2003.

[9] Entech Solutions AS,, "About Entech | Entech," [Online]. Available: https://www.entechteam.com/about-entech. [Accessed February 2023].

[10] E. Team, Interviewee, *Meeting.* [Interview]. January - March 2023.

[11] R. Gulati, Maintenance and Reliability Best Practices, Industrial Press, Incorporated, 2012.

[12] R. D. Cigolini, A. V. Deshmukh, L. Fedele and S. A. McComb, Recent Advances in Maintenance and Infrastructure Management, London: Springer London, 2009.

[13] DET NORSKE VERITAS, "RISK BASED INSPECTION OF OFFSHORE TOPSIDES STATIC MECHANICAL EQUIPMENT," *RECOMMENDED PRACTICE DNV-RP-G101,* p. 13, October 2010.

[14] C. W. BACHMAN, The Programmer as Navigator. Communications of the ACM, 1965.

[15] M. Bartnes, "Safety vs. Security," SINTEF, 2006.

[16] "Risk management — Risk assessment techniques," IEC 31010:2019.

[17] D. Ishikawa, Guide to Quality Control, Tokyo: Asian Productivity, 1986.

[18] M. Singh, K. Øvsthus and A.-L. Kampen, "Development of a Biologically Inspired Condition Management System for Equipment," Western Norway University of Applied Sciences, Bergen , 2023.

[19] S. H. E. S. a. J. C. S. Paul Ringgeberg, "Planning and Execution of Full Scale Tool Tests Increase Reliability in HP/HT Drill Stem Testing," Society of Petroleum Engineers , 1996.

[20] J. Bellarby, Well Completion Design, Elsevier Science, 2009.

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Appendix A – Research paper

Appendix B – Technical drawings

Appendix C – String Diagram

Appendix D – Quality Alert report

Appendix E – Corrosion Test report

Appendix F – FMECA

A Novel Hardware for Managing Deepwater Perforating Contingencies

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Abstract

The upstream oil and gas industry is a highly competitive and rapidly evolving sector characterized by technological innovations that shape its future. Entech Solutions AS strives to establish itself as a leader in this industry by leveraging its expertise in supply chain management, engineering design, project management, and business development. One notable outcome of their expertise is the development of their own Below Packer Safety Joint (BPSJ). The BPSJ serves as a safety mechanism for the tubing-conveyed perforating string, providing customers in this industry with reliability during challenging circumstances. This results in significant savings in terms of both assets and time. To ensure the reliability of their tools and enhance the longevity and cost-effectiveness of the BPSJ, Entech conducts careful analysis and continuous development work. This allows them to deliver dependable solutions to their customers.

1. Introduction

The upstream oil and gas industry is highly competitive and constantly evolving, with new technologies and innovations driving progress and shaping the future of the sector. Entech, a platform for operators and entrepreneurs, aims to be at the forefront of this transformation by providing a space for innovative ideas to be developed and brought to market. The company has established offices in Norway as well as North- and South America.

Entech's work finds its application in offshore drilling operations, particularly in oil reservoirs located in deep water fields. These reservoirs are often geographically remote, necessitating access via drilling platforms or floating production facilities. Given the intricate and demanding nature of deepwater petroleum retrieval, effective exploration and production of these reserves mandates sophisticated technology, technical proficiency, and substantial financial resources. [1]

Well intervention work is essential for safe and reliable petroleum extraction. During this operation a tubing-conveyed perforating string (TCP) is a crucial part. The conditions that a TCP string operates in are in a heavy corrosive brine, high pressures up to 103 MPa, and temperatures that can be anywhere from freezing to 180 °C. These conditions combined with depths of approximately 6000 meters, are some of the most extreme operating conditions that a tool is made to endure. [2]

The process of perforating oil wells involves the creation of small openings in the casing or wellbore to enable the flow of oil and gas into the wellbore. Typically, this is achieved using a perforation gun, which deploys explosive charges to create holes in the casing and surrounding rock formation. During this process pressure differentials occur, leading to equalization where the flow of debris such as sand, chalk, and stone, may flow back towards and into the perforating tool. This influx of debris can clog the steel pipe and cause the perforating gun to become stuck. This represents a significant risk, as the tool string may become lodged several kilometers down the borehole, potentially resulting in the loss of millions of dollars' worth of equipment, and endangering oil wells that may be worth several hundred million dollars. [1]

This paper aims to submit a solution for the problem described above. Entech's new Below Packer Safety Joint (BPSJ) has been developed to solve this problem. BPSJ will be tailored to the specific needs and expectations of their customers. Entech conducts careful reliability analysis and continuous development work, with a focus on sustained performance and longevity.

2. Description of Below Packer Safety Joint (BPSJ)

In the event the tool string becomes lodged several kilometers downhole, the BPSJ is essential to salvage as much of the TCP string as possible. It is therefore equipped with two mechanisms that act as safety guards in the event of this occurrence. The mechanisms Tension Release and Disconnecting are activated to solve the problem.

Tension Release

The first way to address this issue is the safety joint feature that allows it to give a shock or a yank to the string when it yields, making this one of the primary functions of the tool. To make tension and pull the string, the rig tower uses a hydraulic system. Making this tool passive, responding only to external forces.

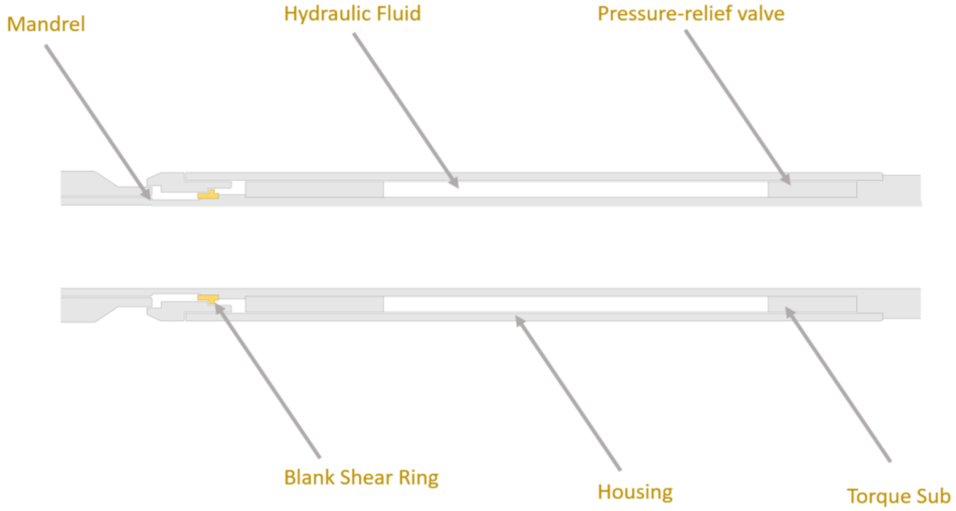
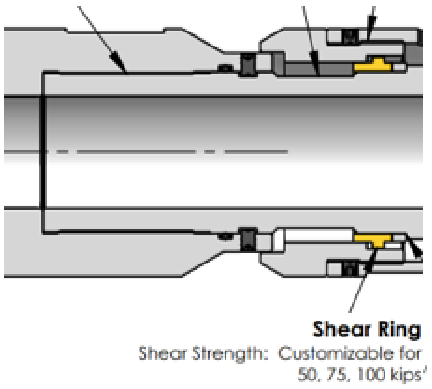


Figure 1 BPSJ

The hydraulic system under consideration comprises of the housing, which serves as a hydraulic cylinder, and a mandrel and torque sub, which functions as the piston. The system includes a reservoir filled with hydraulic fluid that occupies the space between the housing and the mandrel.



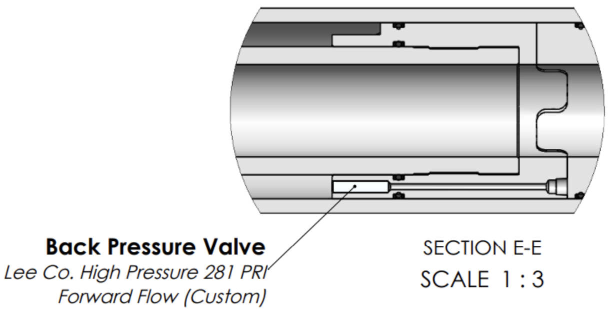
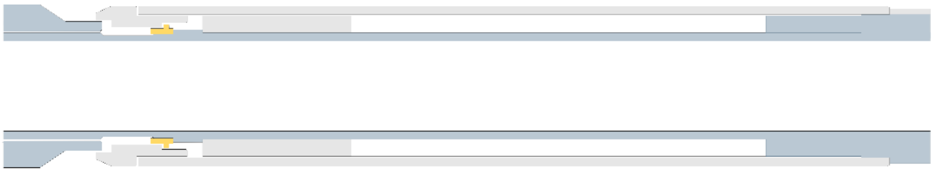


Figure 2 Back Pressure Valve

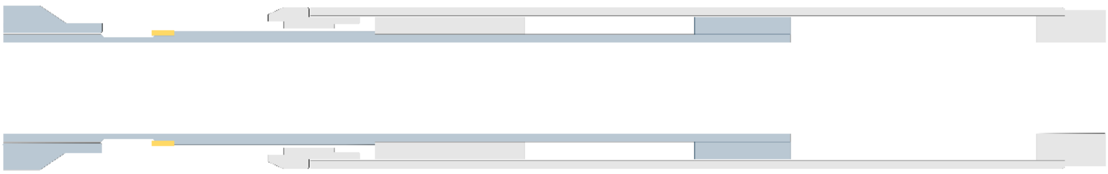
Figure 3 Shear Ring

The activation mechanism for the tool is a shear ring, a specialized component designed to provide a controlled breaking point. Once the ring is subjected to sufficient force from the oil rig, it reaches its shear limit and fractures, allowing the tool to expand. As a result, the teeth of the Torque sub disengage, enabling it and the mandrel to stroke open.

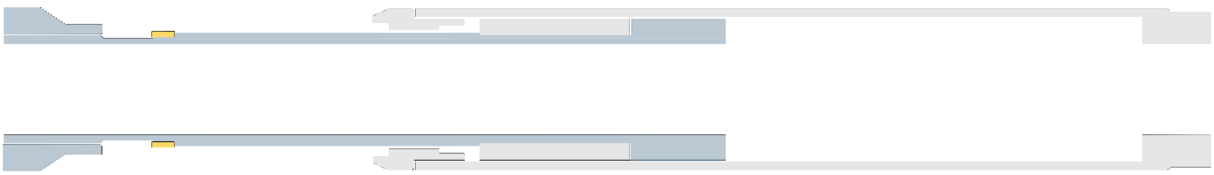
The upward movement of the Torque sub and mandrel creates pressure in the system's hydraulic fluid reservoir, which continues to build until it reaches the set pressure of the pressure-relief valve, at which point the valve opens. Hydraulic fluid then flows into the space between the Torque sub and the Bottom sub, equalizing the pressure. This process repeats several times as the rig continues to pull the string, providing the string with multiple yanks.



Step 1: The strings are hydraulically lifted by the oil rig. The weight from the perforating gun creates so much tension that the shear ring breaks, and the tool is activated.



Step 2: The tool expands, increasing the pressure inside the hydraulic fluid reservoir to the point that the backpressure valve opens and causing yank a on the string.



Step 3: This happens repeatedly until it is no longer possible to build enough pressure in the hydraulic reservoir to open the back pressure valve again.

Step 3: This happens repeatedly until it is no longer possible to build enough pressure in the reservoir to open the back pressure valve again.

Figure 4 Tension Release Process

Disconnecting

The Disconnecting mechanism is the last resort to save the equipment if the string is stuck. It is designed to activate after the Tension Release mechanism fails to work. Once activated, the Disconnecting mechanism ensures that all the equipment located above the BSPJ is saved. However, it is important to note that unlike the Tension Release mechanism, not all the equipment is saved in this process. Therefore, the Disconnecting mechanism is a last resort measure that is put in place to protect the assets.

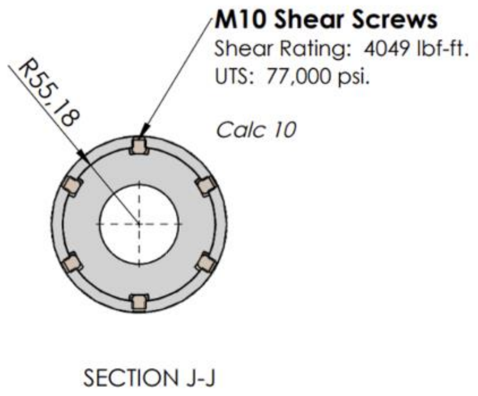


Figure 5 Shear Screws

To understand the Disconnecting mechanism, it is important to have some background knowledge about the whole system in which it operates. The string system is a complex mechanical setup, but an important element for exactly this is the torque rotation. The rotation is applied from the oil rig and causes the string to rotate clockwise when viewed from above. This is also known as a right-hand rotation. It is important to note that this rotation can occur without any part of the string becoming loose or disconnected. This is a critical feature of the design of the Disconnecting mechanism.

Figure 6 Disconnecting Mechanism

The design quality of right rotation in the String system makes it possible to activate the Disconnecting mechanism with a left-hand rotation. When it becomes necessary to activate the Disconnecting mechanism, the entire string is rotated to the left using the torque generated by the oil rig. This rotational movement applies shear forces to the six shear screws located around the perimeter of the housing, which are responsible for holding the housing and sub-base together. After seven turns, the shear forces exceed the predetermined threshold of the screws, causing them to break and resulting in the separation of the housing and bottom sub. The implementation of this separation mechanism enables the efficient retrieval of the string from the well to the rig. This operation ensures the preservation of both the equipment and the well, resulting in potential savings of several hundred million dollars.

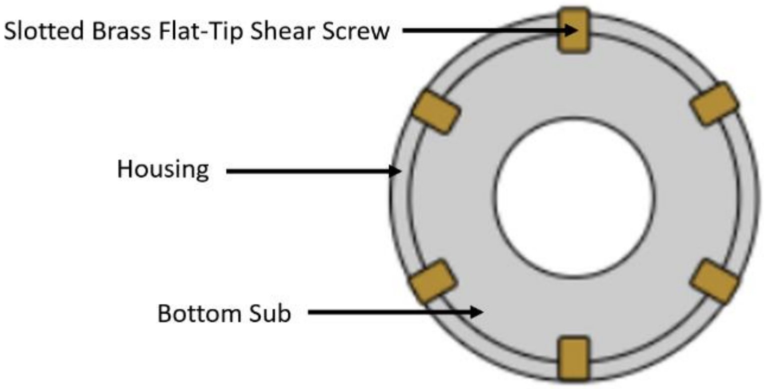


Figure 7 Components in disconnecting function

3. Performance and Lessons Learnt from Campaigns

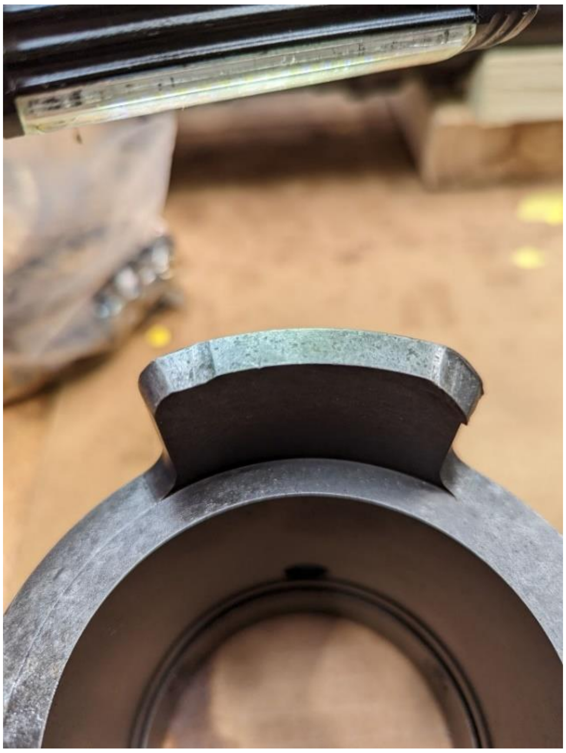
After the tool first campaigns a report on its performance was made, identifying room for improvement leading to further investigation (Appendix C). Cause-and-effect analysis will be used for this investigation, along with an analysis of a specific component that experienced functional failure. The aim is to gain insights and identify potential issues affecting the sub-system (BPSJ) functionality.

Upon retrieval of the tool from the well, it was discovered that the Tension Release had been activated unintentionally and that the BPSJ was stroked open. Tension Release is activated by shearing of the Shear Ring. Given that the mechanism in question can only be employed once, the ring not shearing when intended would defeat the purpose of the tool. Tension Release is not readily available for use when the need arises, further emphasizing the importance of its proper functionality. A further result of post-shearing is that wellbore fluids will flow into the tool, which may cause corrosion damage to other components. It is imperative to conduct a cause-and-effect analysis to comprehensively understand the underlying factors that have contributed to the issue at hand.

One of the main deficiencies identified during the quality alert report was the development of pitting on the Mandrel seal surface. Currently, pitting does not affect tool ratings or specifications. One of the challenges with pitting corrosion is that it can be difficult to detect and monitor, as it often occurs beneath the surface of the material. This issue poses risks to the equipment's integrity and can impair its performance, resulting in unplanned downtime and expensive repairs. Therefore, it was crucial to take measures to address this problem and conduct a cause-and-effect analysis.

Picture 1 Pitting on Mandril

The equipment analysis has revealed another threat to the tool's integrity, it was discovered deformation on the "ears", or the lug/teeth of the Compensating Piston and Torque Sub. The deformation had occurred at the point of contact, on the edge of the teeth. This can have significant consequences, including decreased operational efficiency and potential equipment failure such as the inability to transfer torque. This can result in unplanned downtime, costly repairs, and worst-case scenario- loss of equipment. Addressing this issue is vital, as it could help prevent major equipment failure and ensure that the equipment functions optimally for the duration of its lifespan. Further investigation measures were performed by a Cause-and-effect analysis.



Picture 3 Deformation Top View

Picture 2 Deformation Side View

4. Reliability of Below Packer Safety Joint (BPSJ)

This chapter explores the reliability of the Below Packer Safety Joint (BPSJ) and the steps taken to ensure its optimal performance through a comprehensive Reliability Centered Maintenance (RCM) approach, aimed at providing customers with the best possible tool.

4.a Description of FMECA procedure (highlight unique features)

To achieve the most optimal FMECA, we have incorporated the following elements that outline the distinctive approach taken in implementing the analysis from a safety and security perspective.

Operational Attack	Accident
Operational Hazard: Refers to any potential danger or risk that arises from the normal functioning or operation of a system or equipment. These hazards can arise due to various factors such as equipment malfunction, human error, inadequate maintenance, or environmental factors. **Operational Attack Mechanism:** Refers to a specific method or technique used to exploit safeguards in a system in order to compromise its safety which may cause damage.	**Accident:** An explanation of the potential outcomes that may result from equipment failure during operation or otherwise. It describes the unintended events or series of events that can occur, potentially leading to death, injury, environmental damage, or material harm. [3, p. 599]

Environmental Attack	Incidence
Environmental Threat: Refers to a possibility of harm that arises from external factors and exploits a vulnerability within a system, potentially resulting in unfavorable outcomes. **Environmental Attack Mechanism:** Refers to a specific method or technique used to exploit vulnerabilities in a system in order to compromise its security or cause damage.	**Incidence:** Refers to an event or series of events that have the potential to harm a system, compromising its normal operations and threatening its security. These events may be unwanted or unexpected and have the potential to cause damage or disruptions. Essentially, incidence is a manifestation of a security threat that has materialized and caused actual harm to the system. [4, p. 3]

Risk Analysis
Likelihood of Failure: A category ranking which accounts for the likelihood of a failure taking place with a category ranking of the failure's likelihood as "negligible" (level 1) to a likelihood of "expected" (level 5).
Consequence of Failure: The effect(s) or consequence(s) a failure mode has on an item's operation, functionality, or status. [3, p. 601] A category ranking of the failures worst potential consequence from a level A "slight" (lowest severity) to level E "massive" (highest severity).
Risk Class: Combining the severity ranking and the occurrence ranking in a risk matrix gives an overall risk classification for the item. The items with the highest risk classifications will be selected for further analysis.

To conduct a thorough analysis and minimize the risk of overlooking significant item functions and associated failure modes, it is important to consider different operational modes. By considering the various modes in which the BPSJ operates, a more comprehensive analysis can be conducted, which can help identify failure modes that are specifically related to certain operational modes. This approach creates a strong foundation for identifying and mitigating potential failure modes, ensuring the safe and effective operation of the BPSJ under a variety of conditions. [3, p. 79]

The maintainable items analyzed in the FFA were considered in six different operational modes which are as follows:

- Preparation: Installing in the String
- Operation: Normal
- Operation: Tension Release
- Operation: Disconnecting
- Retrieval: String from Well
- Transportation and Storage: Time Between Campaigns

Figure 8 Operational modes in FFA

4.b Safety and security analysis

This thesis aims to improve the traditional risk evaluation method by adding security to the concept of safety. Safety, security, and survivability engineering are related disciplines that focus on protecting valuable assets from harm caused by accidents or attacks. [5]

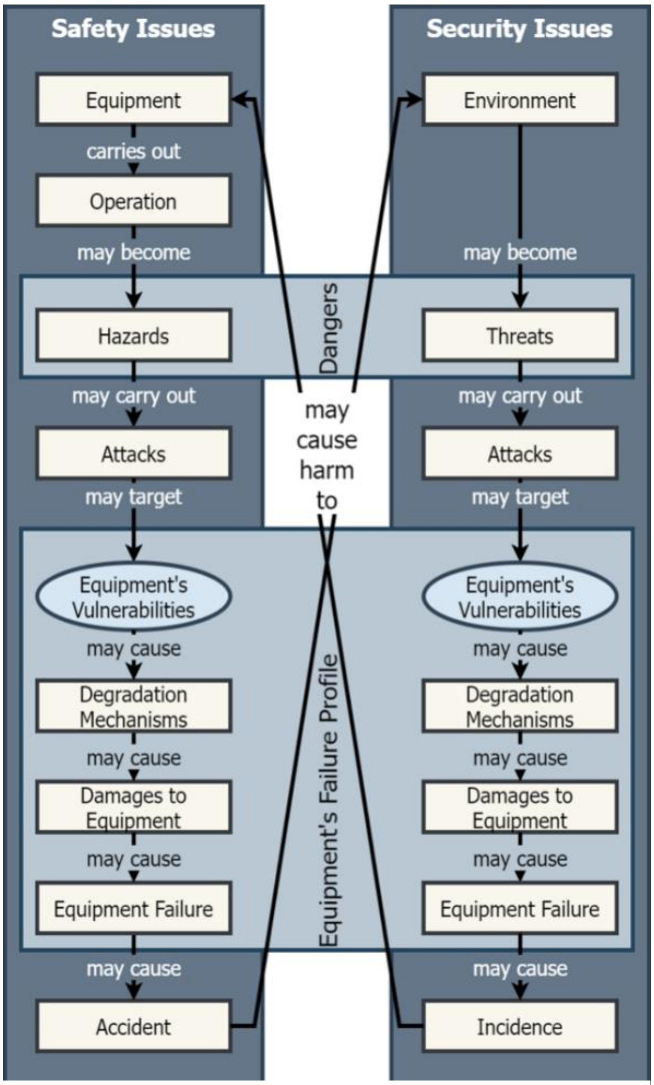


Figure 9 Safety and Security

A part of the aim is to investigate the basis for expanding the already established method for implementing FEMCA. By doing this, new ideas and innovations on the traditional FMECA will be presented. These changes have been implemented by incorporating the concepts of vulnerability, safety, and security into the thesis FMECA analysis. By doing so, a more comprehensive risk assessment has been completed which may have the subsequent effect of improving overall system performance. The FMECA has been divided into two parts: safety and security. Additionally, a detailed assessment of the vulnerability of each maintainable item is included.

In recent years, the field of cybersecurity has become increasingly relevant and important as technology continues to advance. “Safety, security, and survivability engineering are three very closely related disciplines that could greatly benefit from a widespread recognition of their similarities and differences.” [5] It has become apparent that lessons learned from the cybersecurity industry can be applied to other fields, including the further development of FMECA method. FMECA, or Failure Mode, Effects, and Criticality Analysis, is a widely used method for identifying and prioritizing potential failure modes in a system. By drawing inspiration from the cybersecurity industry, we have been able to improve the FMECA method and make it more comprehensive.

One of the key concepts the team has implemented from the cybersecurity industry is the concept of vulnerability. “Survivability vulnerability is a weakness in the system that increases the likelihood that an accident or a successful attack will occur and stop an essential service from being provided.” [5] To implement this concept to the mechanical system, vulnerability refers to the potential for a system to fail due to a specific failure mode. Vulnerability is a quality of a system or of a maintainable item that contributes to a weakness, which may lead to component failure. An example of this may be physical weakness, manufacturing weakness, and so forth. By incorporating the concept of vulnerability into our FMECA analysis, the team is better able to identify and prioritize potential failure modes.

Vulnerability can manifest in a mechanical system through various failure causes, such as design, manufacturing, assembly, or use. To illustrate this, consider the example of a tangential gear. The teeth of the gear represent a point of vulnerability, and their failure can ultimately result in system failure. The following table summarizes the connection between the different failure causes and the resulting vulnerabilities in the system:

Failure	Vulnerability	Failure cause	Description
The teeth break	The teeth	Design	The teeth may be undersized and will not withstand the force applied in the system.
The teeth break	The teeth	Manufacturing	Incorrect heat treatment gears need to be heat-treated to achieve the right level of hardness and strength.
The teeth break	The teeth	Assembly	If the gears are not installed properly, they can experience uneven stress, leading to failure.
The teeth break	The teeth	Use	Over time, the constant meshing of gears can cause wear and tear, which can lead to failure. This is particularly true in high-load applications or when the gears are not lubricated properly.

Table 1 Vulnerability Example

Safety focuses on unintentional events while security also focuses on threats coming from outside the system, often caused by malicious parties as mentioned in the paper Safety vs. security? [4] When integrating these concepts into the FMECA method, it is crucial to understand the difference between safety and security. Safety in cybersecurity relates to the extent to which accidental harm is prevented, detected, and reacted to. Contrarily, security refers to the measures taken to protect a system from intentional harm. By implementing both safety and security measures in an FMECA analysis, we can create a more comprehensive risk assessment and improve overall system performance. These concepts are implemented in a mechanical system with the definitions below.

Safety is the degree to which hazard is prevented, detected, and reacted to. A hazard is an inherent quality of a system that possesses the potential to trigger vulnerabilities within that system, leading to its failure.

Security is the degree to which a threat is prevented, detected, and reacted to. A threat is an inherent quality of the environment that possesses the potential to trigger vulnerabilities within the system, leading to its failure. [6]

The safety part of the FMECA method involves accidents and the security part involves attacks. However, accidents may result in security vulnerabilities which may be exploited by attacks, which will then result in consequences which may fall within the realm of security. In the same manner, attacks may cause safety hazards that result in accidents.

The implementation of safety and security measures in the FMECA method leads to two distinct cycles, each triggered by a unique factor that results in functional failure. The first scenario involves a safety issue, in which the equipment or system initiates an attack on the environment surrounding the underlying hazard. This results in the interference of function failure and subsequent re-implementation of the function failure profile. The second scenario pertains to a security issue, wherein the environment attacks the equipment or system, leading to the interference of function failure and the implementation of the function failure profile.

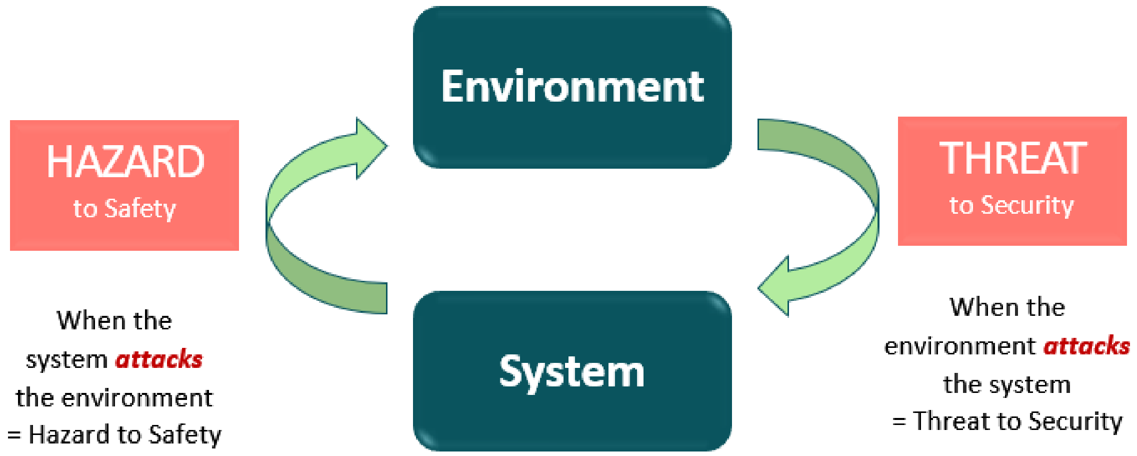


Figure 10 Environment system

4.c Representative results of analysis

To optimize the tools durability multiple analyses were conducted, such as a functional analysis system technique (FAST), cause- and effect analysis as well as identifying the tools interfaces. The results of the FAST diagram were that the tool has two primary functions described in chapter 2. [3, p. 77] Below is an illustration of the functions of the BPSJ.

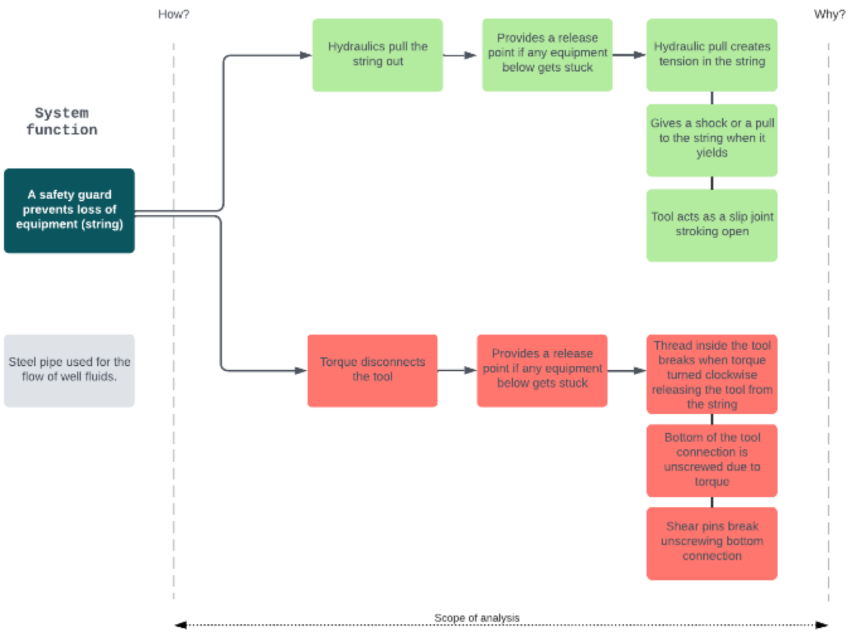


Figure 11 System Function

The results of the identification of the system interfaces (appendix B.1). The sub-system 27 is representative of the BPSJ. The analysis resulted in understanding how the tool is affected by the environment it operates in, as well as how the tool affects its surrounding environment.

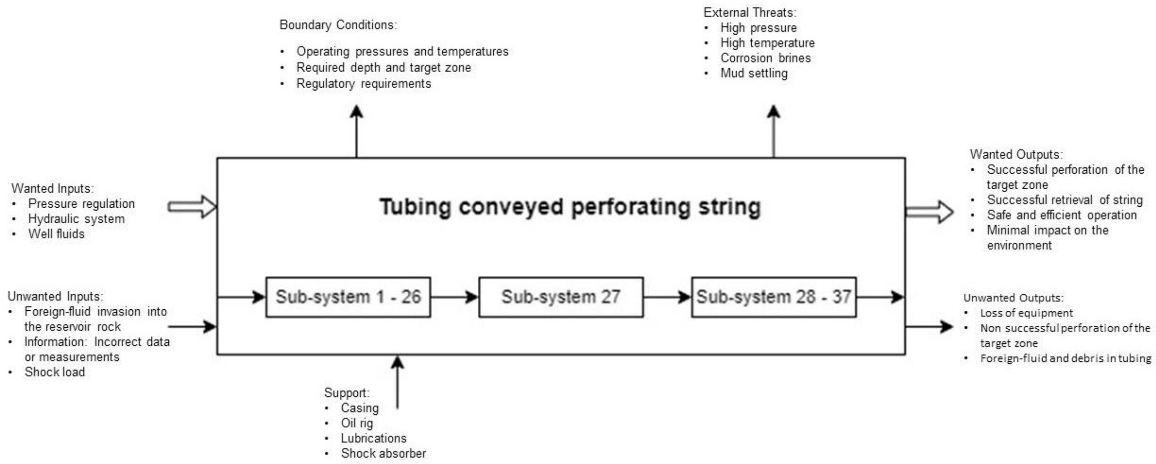


Figure 12 System Interface

In the Failure Mode, Effects, and Criticality Analysis the items that have been identified as critical are subjected to further analysis. Each of these items undergoes a comprehensive evaluation, with a criticality assessment conducted for both safety and security considerations. The FMECA worksheet provides an overview of the potential failure modes associated with these items, as well as any corresponding functional failures. To further illustrate the findings of this analysis, a condensed version of the completed FMECA worksheet is illustrated below. The complete analysis is included in attachment 1.

Maintainable Item		Bottom Sub				
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operartion: Tension Release	Operation: Disconnecting	Transportation and Storage: Time between campaigns
Function Failure Analysis	Function	Secure components together	Secure components together	Handle predetermined torque and withstand tension load	Disconnect from the rest for BPSJ	Maintain component integrity
	Function Failure	Movement or a total separation at the point of attachment	Movement or a total separation at the point of attachment	Movement or a total separation at the point of attachment	Housing not releasing from the bottom sub	Component integrity compromised
	Vulnerability	Structural deficiency because of * material of construction * chamfering, fillet and rounding Connections because of * weak threads and screws * sealing	Structural deficiency because of * material of construction * chamfering, fillet and rounding * mud, debree buildup Connections because of * weak threads and screws * sealing	Structural deficiency because of * material of construction * chamfering, fillet and rounding * mud, debree buildup Connections because of * weak threads and screws * sealing	Structural deficiency because of * material of construction * chamfering, fillet and rounding Connections because of * weak threads and screws	Structural deficiency because of * material of construction * chamfering, fillet and rounding Connections because of * weak threads and screws * sealing
	Failure Effect	Release at connection points at unintended time	Release at unintended time	Release at unintended time	Non-release	Release at unintended time
Operational Attack	Operational Hazard	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention. Physical - Loss of sealing - leakage of hydraulic fluid	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical: unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.
	Operational Attack Mechanism	Mechanical - Deformation of components Physical - Loss of pressure and influx of well fluid	Mechanical - Deformation of components	Mechanical - Deformation of components	Mechanical - Deformation of components	Mechanical: deformation of components
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material * Manufacturing - fabrication and assembly * Usage - Human error	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure
	Equipment Failure Mechanism	1.3 Clearance / alignment failure 1.4 Deformation 2.5 Breakage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage
	Equipment Failure Mode	FCO: Failure to connect	FTD: Failure to disconnect	FTD: Failure to disconnect	FTD: Failure to disconnect	FCO: Failure to connect
	Equipment Failure Characteristics	Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Accident		Deformation of equipment connection points and leakage.	FTD: The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.
Environmental Attack	Environmental Threat	Mechanical: deformation hinder the placement/setting of tool to the string.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.
	Environmental Attack Mechanism	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Mechanical: compromised mechanical properties of the BottumSub necessitate the redistribution of the workload to other components, resulting in the inability to achieve the intended function solely through the use of these components.	Mechanical: compromised mechanical properties of the BottumSub necessitate the redistribution of the workload to other components, resulting in the inability to achieve the intended function solely through the use of these components.	Mechanical: compromised mechanical properties of the BottumSub necessitate the redistribution of the workload to other components, resulting in the inability to achieve the intended function solely through the use of these components.	Mechanical: compromised mechanical properties of the BottumSub necessitate the redistribution of the workload to other components, resulting in the inability to achieve the intended function solely through the use of these components.
Incidence		Deformation of equipment limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.
Criticality Analysis	Likelihood of Failure	2 - Low	1 - Negligble	2 - Low	2 - Low	4 - High
	Consequence of Failure	B - Minor	D - Major	D - Major	D - Major	B - Minor
	Risk Class	1 - Pass	1 - Pass	2 - Pass with Condition(s)	2 - Pass with Condition(s)	2 - Pass with Condition(s)

Table 2 FMECA Safety

Maintainable Item		Bottom Sub				
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operartion: Tension Release	Operation: Disconnecting	Transportation and Storage: Time between campaigns
Function Failure Analysis	Function	Secure components together	Secure components together	Handle predetermined torque and withstand tension load	Disconnect from the rest for BPSJ	Maintain component integrity
	Function Failure	Movement or a total separation at the point of attachment	Movement or a total separation at the point of attachment	Movement or a total separation at the point of attachment	Housing not releasing from the bottom sub	Component integrity compromised
	Vulnerability	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity, the thread are specifically exposed.	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity, the threads are specifically exposed. *Thermal: Loss of strength and composition due to high temperature variation.	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity, the threads are specifically exposed. *Thermal: Loss of strength and composition due to high temprature variation.	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity, the threads are specifically exposed. *Thermal: Loss of strength and composition due to high temprature variation.	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity, the thread are specifically exposed.
	Failure Effect	Release at unintended time	Release at unintended time	Release at unintended time	Non-release	Release at unintended time
Environmental Attack	Environmental Threat	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation
	Environmental Attack Mechanism	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact *Thermal - Non-optimal mechanics of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure
	Equipment Failure Mechanism	2.2 Corrosion 2.5 Breakage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue 5.3 Misc. External influence	2.2 Corrosion 2.5 Breakage 2.6 Fatigue 5.3 Misc. External influence	2.2 Corrosion 2.5 Breakage 2.6 Fatigue 5.3 Misc. External influence	2.2 Corrosion 2.5 Breakage
	Equipment Failure Mode	FCO: Failure to connect	FTD: Failure to disconnect	FTD: Failure to disconnect	FTD: Failure to disconnect	FCO: Failure to connect
	Equipment Failure Characteristics	Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Incidence		Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	FCO: Failure to connect
Operational Attack	Operational Hazard	* Mechanical - Corroded part may result in weak structure * Mechanical - Deformed part may result in improper securing	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure * Thermal - Temperature variations may lessen the materials structural integrity.	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure * Thermal - Temperature variations may lessen the materials structural integrity.	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure * Thermal - Temperature variations may lessen the materials structural integrity.	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure
	Operational Attack Mechanism	* Mechanical - Weak structure may result in breakage * Mechanical - Improper securing may result in disconnect	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage * Thermal - Compromised structural integrity resulting in fracture	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage * Thermal - Compromised structural integrity resulting in fracture	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage * Thermal - Compromised structural integrity resulting in fracture	Chemical - Corrosion may lead to material damage Mechanical - Weak structur may lead to breakage in not indented places
Accident		Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.
Criticality Analysis	Likelihood of Failure	3 - Medium	1 - Negligble	1 - Negligble	1 - Negligble	1 - Negligble
	Consequence of Failure	A - Slight	E - Massive	E - Massive	E - Massive	C - Moderate
	Risk Class	1 - Pass	2 - Pass with Condition(s)	2 - Pass with Condition(s)	2 - Pass with Condition(s)	1 - Pass

Table 3 FMECA Security

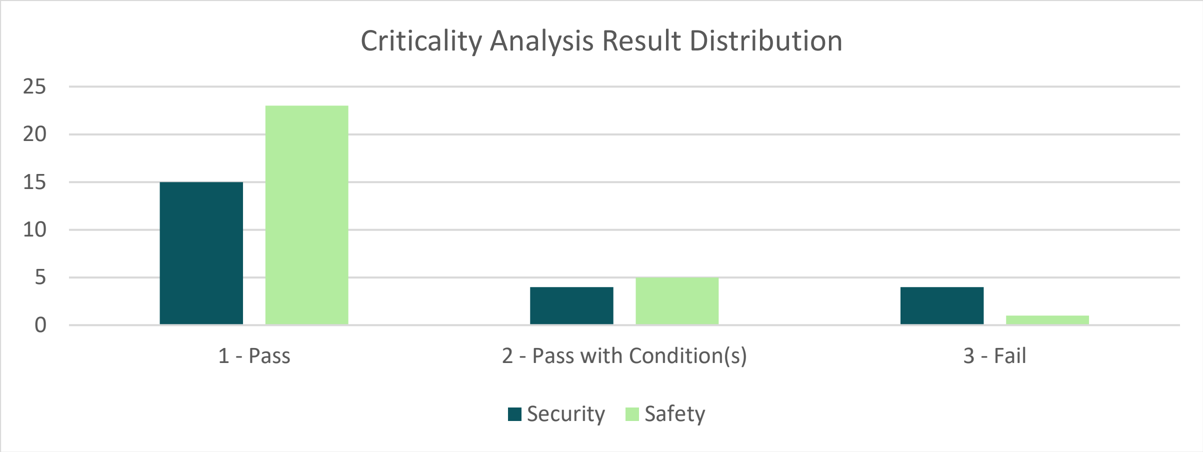


Table 4 Criticality Result

Based on the FMECA criticality analysis components were classified as either 1-Pass, 2-Pass with Condition(s), or 3- Fail. Components which were classified as 3-Fail went on for further consideration by the way of a cause- and effect analysis.

The diagram below illustrates the cause-and-effect analysis that was performed to identify the root causes and effects of tension release mechanism activated unnecessarily.

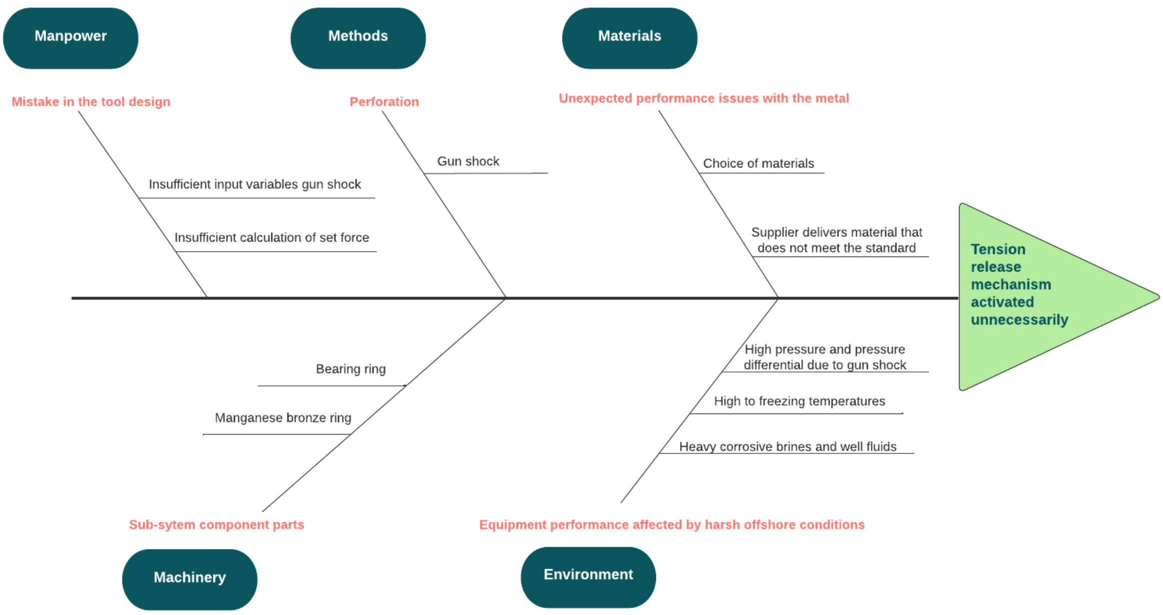


Figure 13 Fishbone - Tension Release

Fishbone analysis identified perforation and resultant forces from gun impacts as potential contributing factors to the failure. The sudden increase in axial load and weight due to gun shock was considered a possible cause for the shearing of the shear ring and subsequent opening of the BPSJ. Potential solutions discussed with Entech, and their customer included increasing the shearing value of the ring by increasing the contact area and redesigning components within the tool to incorporate shock absorption mechanisms. Balancing the shearing value and incorporating dampening mechanisms can prolong the tool's lifespan and minimize damage to other components, although complete elimination of the problem is challenging due to dynamic effects in the well.

The following diagram depicts the results of a cause-and-effect analysis conducted to identify the causes and effects of deformation.

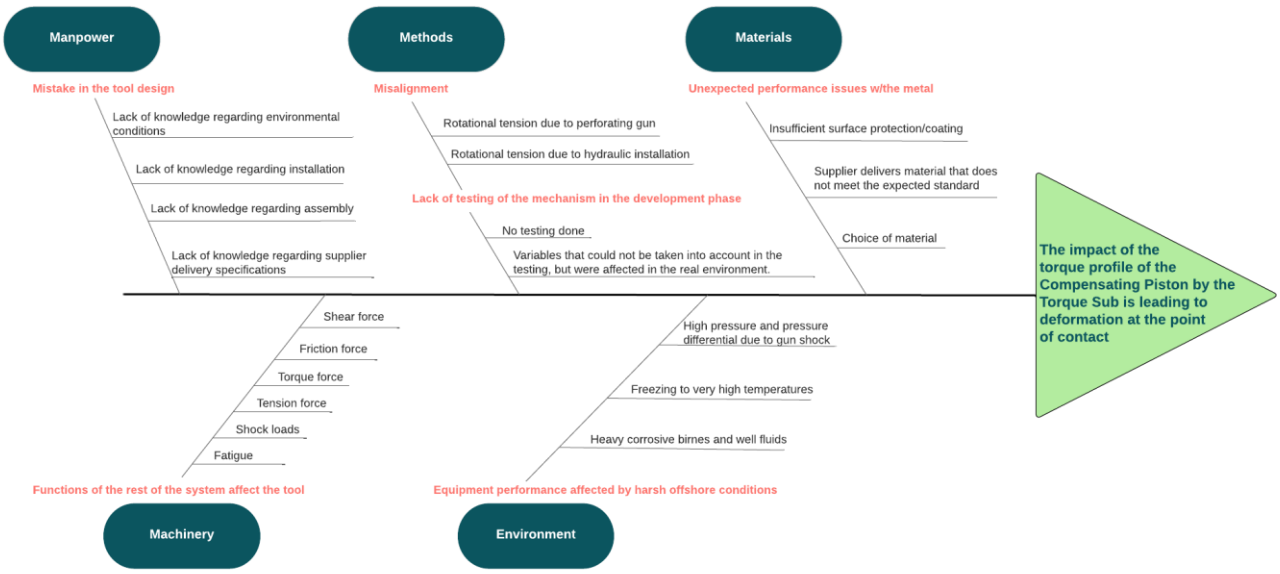


Figure 14: Fishbone diagram - Misalignment

The Fishbone analysis identified misalignment as the cause of deformation in the Compensating Piston and Torque Sub. The misalignment resulted from rotational tension generated during tool string descent, leading to collision of the components causing flaring. Proposed solutions discussed in a joint meeting included redesigning the teeth by increasing their number and implementing an angle force transfer profile. Further testing is needed to determine the most effective solution and prevent future failures.

The diagram presented below illustrates the outcomes of a cause-and-effect analysis that was performed to identify the root causes and effects of pitting and corrosion on Mandrel seal surface.

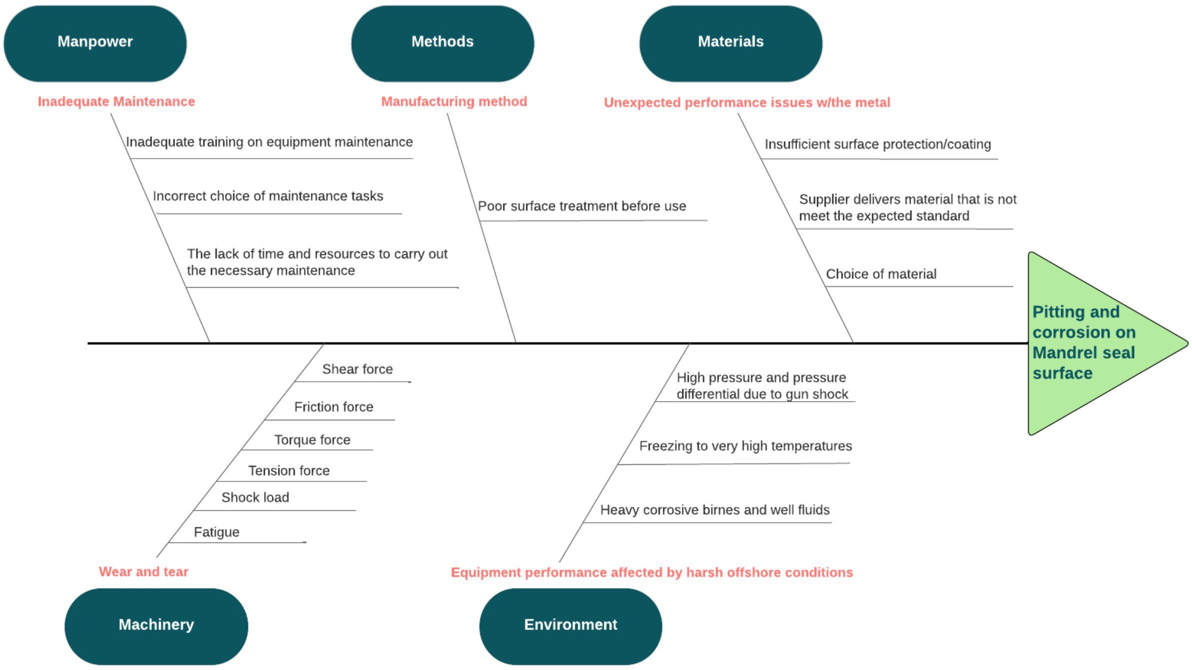
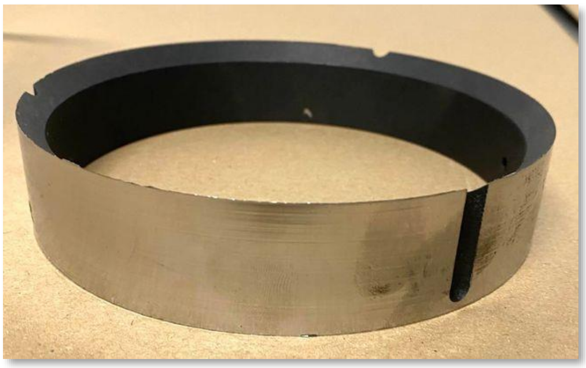


Figure 15: Fishbone diagram Corrosion

The fishbone analysis hypothesized that pitting occurs not due to liquid submersion, but rather after retrieval from the well when the tool is exposed to oxygen. Specifically, the BPSJ sometimes sits on a platform for multiple days after retrieval without being rinsed with fresh water. The tool may then spend an additional two days on a boat whilst heading back to land, during which time it will be rinsed with seawater but then left to sit on the shore in the sun for a couple more days, before being returned to the operations base for maintenance. These conditions are believed to promote the corrosion and pitting of the BPSJ's surface, which can compromise its performance and longevity. [1] Furthermore, this hypothesis will be investigated with Corrosion testing.

A laboratory experiment was conducted to test the hypothesis identified in the Fishbone analysis regarding pitting corrosion. The experiment aimed to understand the factors contributing to corrosion and propose potential solutions to mitigate its occurrence. The necessary conditions for corrosion (metal, water or electrolyte, and a corrodent) were present, especially after retrieval of the tool exposed to seawater and well fluid. Three metal rings made of ASIS 4140 were tested, coated on the inside and untreated on the outside. Well fluids (Potassium Chloride, Calcium chloride, Calcium Bromide) were used to simulate the tool's operational environment. The rings were submerged in the fluids, visually inspected, and then partially exposed to oxygen to simulate string retrieval. Corrosion was observed on the exposed parts, while the submerged parts showed less corrosion. Two inspections were conducted during the testing period, revealing discoloration, an unknown black liquid, and increased corrosion on the exposed portions.



Picture 4 Metal Ring

The experiment concluded that the rate of corrosion significantly increased when the metal rings were exposed to oxygen after retrieval. This finding indicates that the tool is most vulnerable to corrosion during transportation rather than during operation. To mitigate this, it is recommended to thoroughly rinse the tool immediately after retrieval and keep it protected from exposure to sunlight. Additionally, applying a protective coating can enhance the tool's longevity and effectiveness.

Picture 5 End Results

To address the tool's vulnerability to corrosion, research was conducted to find suitable surface treatments. A company in Houston, Texas, with a diverse coating portfolio was consulted. Environmental conditions such as temperature variations, CO_2 exposure, hydrocarbon exposure, and corrosive brines were considered. Various coatings including electroless nickel, SBN-QPQ, epoxy, and molybdenum disulfide were evaluated. The QPQ coating was highly recommended for its superior properties, including hardness, durability, and corrosion resistance. Applying this surface treatment can protect the seal surface and potentially extend the mandrel's useful lifespan.

4.d Recommendations for maintenance and modifications

Recognized industry standards were applied to ensure maintenance activities align with industry best practices. Inspection maintenance intervals for the BPSJ occur before installation and after retrieval of the string, in between campaigns. Items were classified as "pass with condition(s)" or "fail" during operational assessments.

Safety		Criticality Analysis	
Item	Mode	Risk Class	Risk Management Measures
Bottom Sub	3	2 - Pass with Condition(2)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Inspect for damage every time the tool is run in the wellbore, disassmbled, transported, or handled. * Clean and inspect all sealing surfaces for minor pits and scratches. If pits and scratches are visible, remove with an emery cloth. * Clean and inspect threaded surfaces for damage such as deformation, stripping, or burrs. * Ensure the correct size o-rings and backup rings.
	4	2 - Pass with Condition(2)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Inspect for damage every time the tool is run in the wellbore, disassmbled, transported, or handled. * Clean and inspect all sealing surfaces for minor pits and scratches. If pits and scratches are visible, remove with an emery cloth. * Clean and inspect threaded surfaces for damage such as deformation, stripping, or burrs. * Ensure the correct size o-rings and backup rings.
	6	2 - Pass with Condition(2)	9. Inspection * Inspect for damage every time the tool is run in the wellbore, disassmbled, transported, or handled. * Clean and inspect all sealing surfaces for minor pits and scratches. If pits and scratches are visible, remove with an emery cloth. * Clean and inspect threaded surfaces for damage such as deformation, stripping, or burrs. * Ensure the correct size o-rings and backup rings.

Table 5 Maintenance Actions – Safety

Security		Criticality Analysis	
Item	Mode	Risk Class	Recommended actions(s)
Bottom Sub	2	2 - Pass with Condition(2)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Close visual inspection of the threads for damages such as deformation, stripping, or burrs. * Disassemble, inspect, and deep clean the component. * Remove contaminants and residual wellbore fluid. * Thoroughly dry componet and apply a corrosion inhibitor. * Outside storing: fully assembled with all seals and thread protectors. * Do not store on the ground. * Store in climate controlled environment or outside under a cover submerged in 0-ring friendly corrosion inhibitor fluid.
	3	2 - Pass with Condition(2)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Close visual inspection of the threads for damages such as deformation, stripping, or burrs. * Disassemble, inspect, and deep clean the component. * Remove contaminants and residual wellbore fluid. * Thoroughly dry componet and apply a corrosion inhibitor. * Outside storing: fully assembled with all seals and thread protectors. * Do not store on the ground. * Store in climate controlled environment or outside under a cover submerged in 0-ring friendly corrosion inhibitor fluid.
	4	2 - Pass with Condition(2)	9. Inspection - Inspection only made possible when the BPSJ is in-between campaigns. * Close visual inspection of the threads for damages such as deformation, stripping, or burrs. * Disassemble, inspect, and deep clean the component. * Remove contaminants and residual wellbore fluid. * Thoroughly dry componet and apply a corrosion inhibitor. * Outside storing: fully assembled with all seals and thread protectors. * Do not store on the ground. * Store in climate controlled environment or outside under a cover submerged in 0-ring friendly corrosion inhibitor fluid.

Table 6 Maintenance Actions - Security

4.e Modified parts of the tool

Entech enhanced the design of the Compensating Piston and Torque Sub to address misalignment, resulting in improved force distribution. The modification notably increased the contact area between the two parts by a factor of six.

In order to enhance durability, the Compensating Piston and Torque Sub underwent a surface treatment process known as Quench-Polish-Quench (QPQ), which adds hardness to the parts. This treatment aims to significantly improve their longevity.

Picture 6 The Redesign

Moreover, Entech is currently implementing electroless nickel surface protection on the housing and mandrel. This protective measure offers outstanding corrosion resistance, thermal stability, surface hardness, and wear protection. Additionally, it substantially extends the lifespan of stainless-steel components.

[7, p. 7]

Conclusions

In conclusion, Entech Solutions AS has developed the Below Packer Safety Joint (BPSJ) as a reliable and efficient solution for the challenges faced in the upstream oil and gas industry. The BPSJ serves as a safety mechanism for the tubing-conveyed perforating string, offering customers reliability and significant savings in terms of assets and time. The Tension Release mechanism of the BPSJ provides a shock or yank to the string when it yields, ensuring its proper functionality even in extreme operating conditions. The Disconnecting mechanism acts as a last resort measure to save the equipment in case the Tension Release mechanism fails.

Through performance analysis and lessons learned from campaigns, areas for improvement have been identified, including issues with the Tension Release and the development of pitting on the Mandrel seal surface. Deformation on the "ears" of the Compensating Piston and Torque Sub has also been observed, emphasizing the importance of addressing these concerns to prevent major equipment failure.

To ensure the reliability of the BPSJ, Entech conducts a Reliability-Centered Maintenance Analysis (RCM) that incorporates elements such as operational hazards, attack mechanisms, accidents, and environmental threats. By considering different operational modes and implementing a comprehensive risk assessment, potential failure modes can be identified and mitigated effectively.

The integration of safety and security analysis into the FMECA method has further enhanced the evaluation process. By incorporating the concept of vulnerability, potential weaknesses in the system can be identified and prioritized, leading to improved overall system performance. Lessons learned from the cybersecurity industry have been applied to enhance the FMECA method and make it more comprehensive, ensuring a thorough assessment of the BPSJ's reliability.

In conclusion, the development of the BPSJ by Entech Solutions AS represents a significant contribution to the upstream oil and gas industry. The company's commitment to continuous improvement and careful analysis ensures the delivery of dependable solutions to customers, ultimately enhancing the safety, efficiency, and cost-effectiveness of oil well intervention operations.

References

[1] E. Team, Interviewee, *Meeting.* [Interview]. January - March 2023.

[2] S. H. E. S. a. J. C. S. Paul Ringgeberg, «Planning and Execution of Full Scale Tool Tests Increase Reliability in HP/HT Drill Stem Testing,» Society of Petroleum Engineers , 1996.

[3] M. Rausand og A. Høyland, System Reliability Theory Models, Statistical Methods, and Applications, Wiley, 2004.

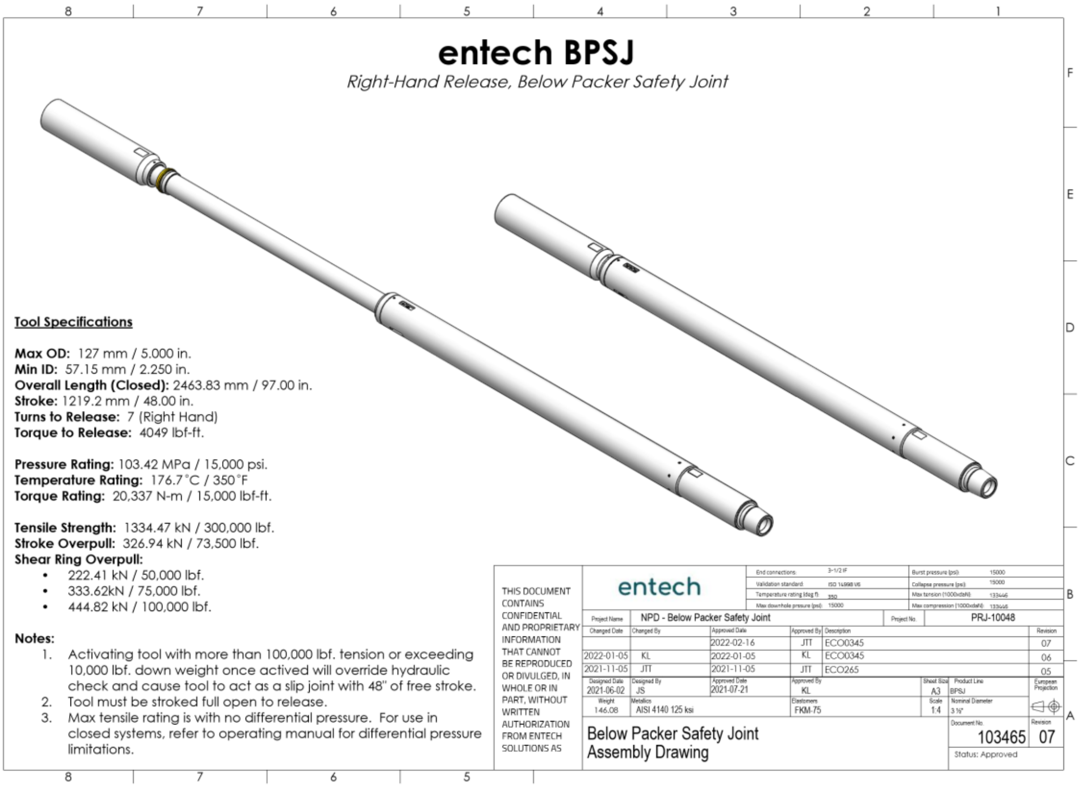
[4] M. Bartnes, «Safety vs. Security,» SINTEF, 2006.

[5] D. Firesmith, «Common Concepts Underlying Safety, Security, and Survivability Engineering,» Carnegie Mellon University, 2003.

[6] M. Singh, K. Øvsthus og A.-L. Kampen, «Development of a Biologically Inspired Condition Management System for Equipment,» Western Norway University of Applied Sciences, Bergen , 2023.

[7] W. K. S. Fürbeth, Corrosion - Protection of Structural Metas and Alloys, Trans Tech Publications., 2019.

B.1



entech BPSJ
Right-Hand Release, Below Packer Safety Joint
Tool Specifications
Max OD: 127 mm / 5.000 in.
Min ID: 57.15 mm / 2.250 in.
Overall Length (Closed): 2463.83 mm / 97.00 in.
Stroke: 1219.2 mm / 48.00 in.
Turns to Release: 7 (Right Hand)
Torque to Release: 4049 lbf-ft.
Pressure Rating: 103.42 MPa / 15,000 psi.
Temperature Rating: 176.7°C / 350°F
Torque Rating: 20,337 N-m / 15,000 lbf-ft.
Tensile Strength: 1334.47 kN / 300,000 lbf.
Stroke Overpull: 326.94 kN / 73,500 lbf.
Shear Ring Overpull:
• 222.41 kN / 50,000 lbf.
• 333.62kN / 75,000 lbf.
• 444.82 kN / 100,000 lbf.
Notes:
1. Activating tool with more than 100,000 lbf. tension or exceeding 10,000 lbf. down weight once actived will override hydraulic check and cause tool to act as a slip joint with 48" of free stroke.
2. Tool must be stroked full open to release.
3. Max tensile rating is with no differential pressure. For use in closed systems, refer to operating manual for differential pressure limitations.
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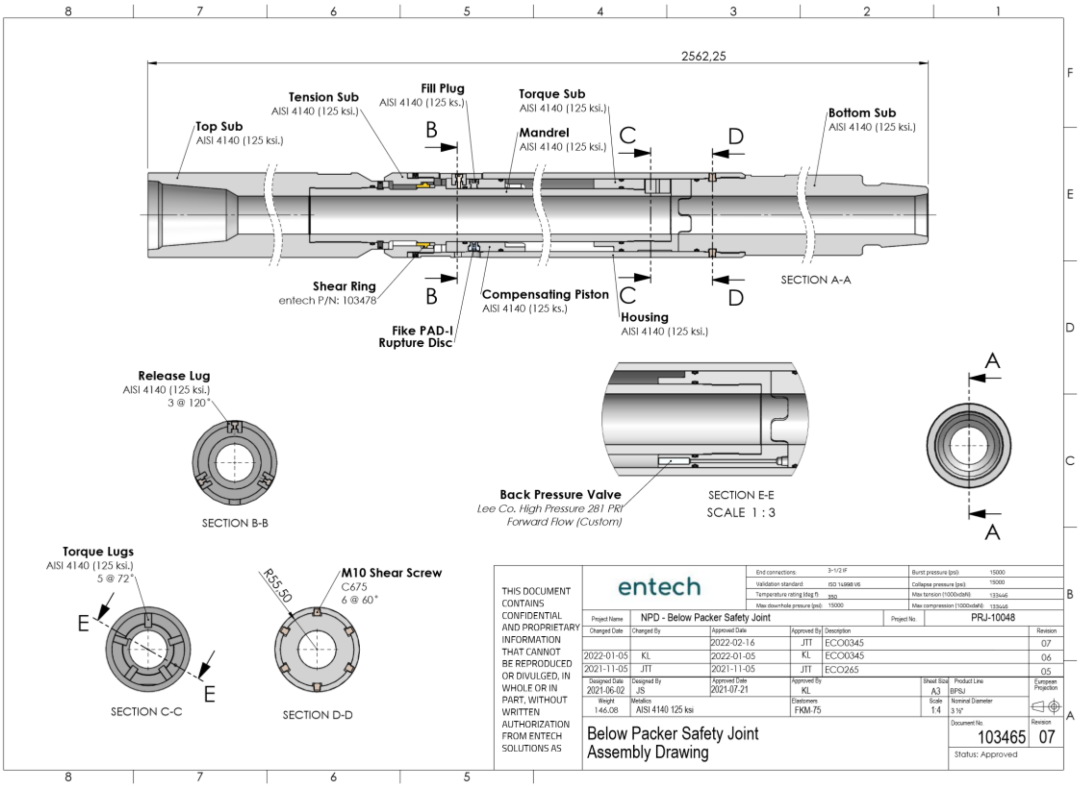
entech
End connections: 3-1/2 IF
Validation standard: ISO 14998 V6
Temperature rating (deg f): 350
Max downhole presure (psi): 15000
Burst pressure (psi): 15000
Collapse pressure (psi): 15000
Max tension (1000xdaN): 133446
Max compression (1000xdaN): 133446
Project Name NPD - Below Packer Safety Joint
Project No. PRJ-10048
Changed Date | Changed By | Approved Date | Approved By | Description | Revision
2022-02-16 | JTT | ECO0345 | 07
2022-01-05 | KL | 2022-01-05 | KL | ECO0345 | 06
2021-11-05 | JTT | 2021-11-05 | JTT | ECO265 | 05
Designed Date 2021-06-02
Designed By JS
Approved Date 2021-07-21
Approved By KL
Sheet Size A3
Product Line BPSJ
Weight 146.08
Metallics AISI 4140 125 ksi
Elastomers FKM-75
Scale 1:4
Nominal Diameter 3 ½"
European Projection
Below Packer Safety Joint
Assembly Drawing
Document No. 103465
Revision 07
Status: Approved

B.2



2562,25
Tension Sub
AISI 4140 (125 ksi.)
Fill Plug
AISI 4140 (125 ksi.)
Torque Sub
AISI 4140 (125 ksi.)
Top Sub
AISI 4140 (125 ksi.)
Mandrel
AISI 4140 (125 ksi.)
Bottom Sub
AISI 4140 (125 ksi.)
Shear Ring
entech P/N: 103478
Compensating Piston
AISI 4140 (125 ks.)
Housing
AISI 4140 (125 ksi.)
Fike PAD-I
Rupture Disc
SECTION A-A
Release Lug
AISI 4140 (125 ksi.)
3 @ 120°
SECTION B-B
Back Pressure Valve
Lee Co. High Pressure 281 PRI
Forward Flow (Custom)
SECTION E-E
SCALE 1 : 3
Torque Lugs
AISI 4140 (125 ksi.)
5 @ 72°
SECTION C-C
R55.50
M10 Shear Screw
C675
6 @ 60°
SECTION D-D
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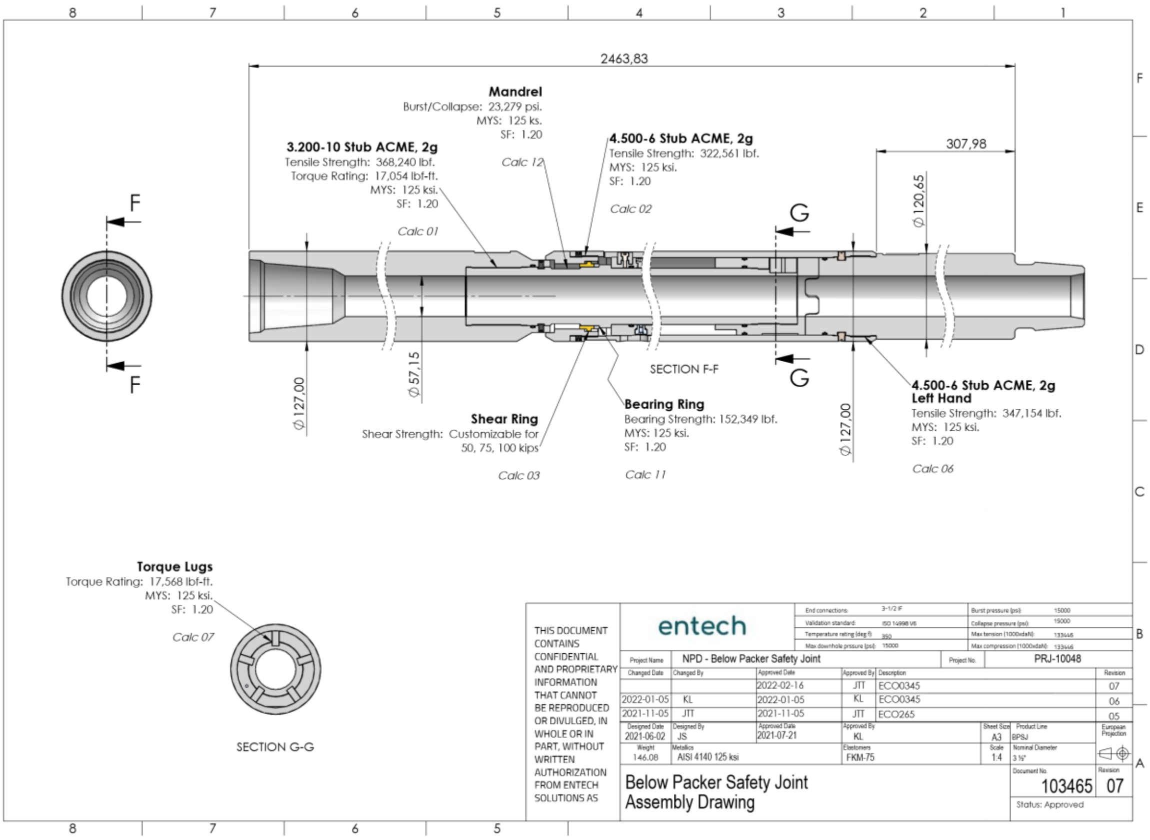
Project Name NPD - Below Packer Safety Joint
Project No. PRJ-10048
2022-02-16 | JTT | ECO0345 | 07
2022-01-05 | KL | 2022-01-05 | KL | ECO0345 | 06
2021-11-05 | JTT | 2021-11-05 | JTT | ECO265 | 05
Below Packer Safety Joint
Assembly Drawing
Document No. 103465
Revision 07
Status: Approved

B.3



2463,83
Mandrel
Burst/Collapse: 23,279 psi.
MYS: 125 ks.
SF: 1.20
Calc 12
3.200-10 Stub ACME, 2g
Tensile Strength: 368,240 lbf.
Torque Rating: 17,054 lbf-ft.
MYS: 125 ksi.
SF: 1.20
Calc 01
4.500-6 Stub ACME, 2g
Tensile Strength: 322,561 lbf.
MYS: 125 ksi.
SF: 1.20
Calc 02
307,98
Ø 120,65
F
G
Ø 127,00
Ø 57,15
SECTION F-F
Shear Ring
Shear Strength: Customizable for
50, 75, 100 kips
Calc 03
Bearing Ring
Bearing Strength: 152,349 lbf.
MYS: 125 ksi.
SF: 1.20
Calc 11
4.500-6 Stub ACME, 2g
Left Hand
Tensile Strength: 347,154 lbf.
MYS: 125 ksi.
SF: 1.20
Calc 06
Torque Lugs
Torque Rating: 17,568 lbf-ft.
MYS: 125 ksi.
SF: 1.20
Calc 07
SECTION G-G
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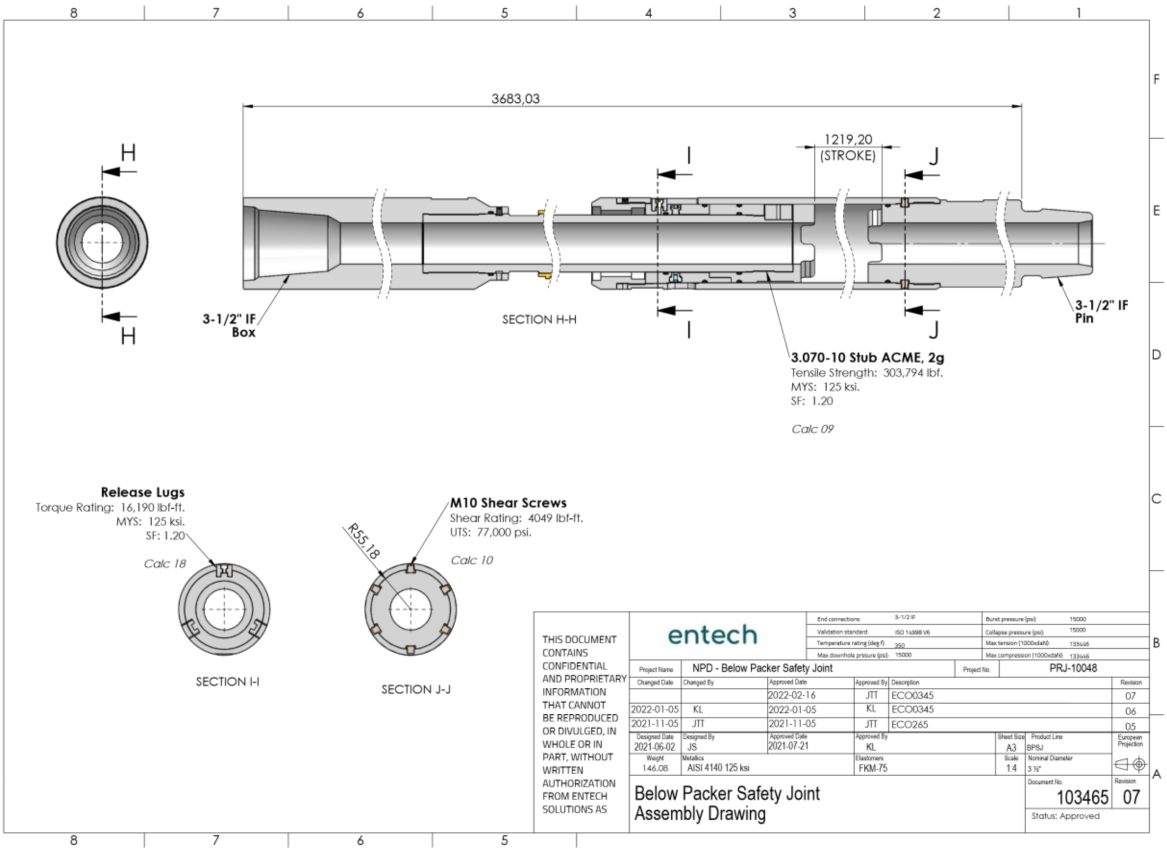
Project Name NPD - Below Packer Safety Joint
PRJ-10048
2022-02-16 JTT ECO0345 07
2022-01-05 KL 2022-01-05 KL ECO0345 06
2021-11-05 JTT 2021-11-05 JTT ECO265 05
2021-06-02 JS 2021-07-21 KL A3 BPSJ
146.08 AISI 4140 125 ksi FKM-75 1:4 3 ½"
Below Packer Safety Joint
Assembly Drawing
103465 07
Status: Approved

B.4



3683,03
1219,20
(STROKE)
H
I
J
3-1/2" IF
Box
SECTION H-H
3-1/2" IF
Pin
3.070-10 Stub ACME, 2g
Tensile Strength: 303,794 lbf.
MYS: 125 ksi.
SF: 1.20
Calc 09
Release Lugs
Torque Rating: 16,190 lbf-ft.
MYS: 125 ksi.
SF: 1.20
Calc 18
SECTION I-I
M10 Shear Screws
Shear Rating: 4049 lbf-ft.
UTS: 77,000 psi.
R55,18
Calc 10
SECTION J-J
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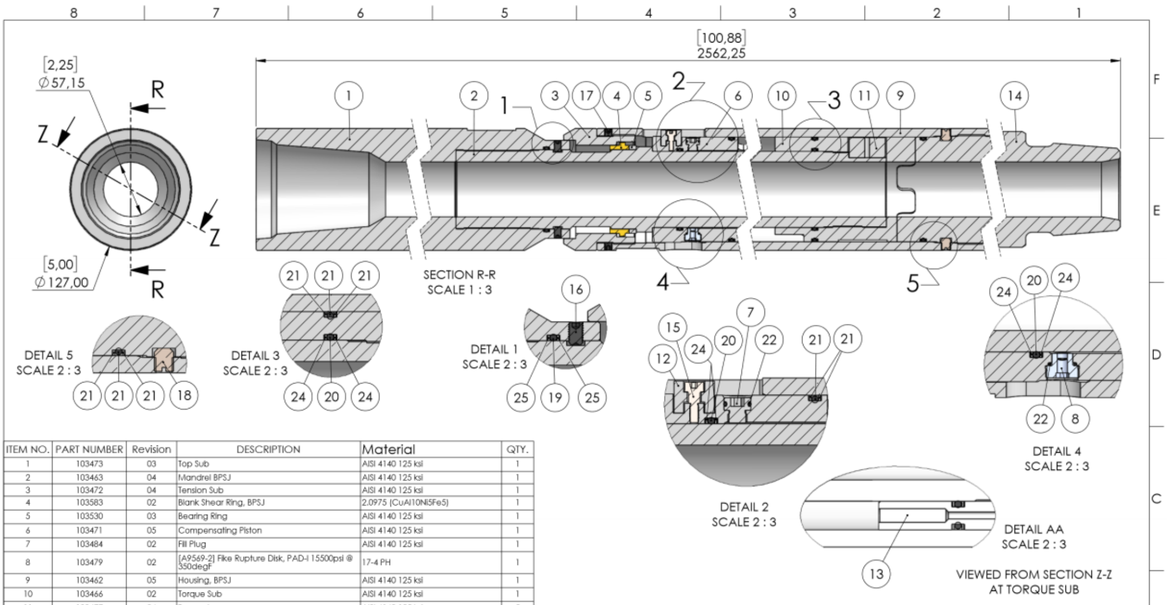
entech
Project Name NPD - Below Packer Safety Joint
PRJ-10048
2022-02-16 JTT ECO0345 07
2022-01-05 KL 2022-01-05 KL ECO0345 06
2021-11-05 JTT 2021-11-05 JTT ECO265 05
2021-06-02 JS 2021-07-21 KL A3 BPSJ
146.08 AISI 4140 125 ksi FKM-75 1:4 3 ½"
Below Packer Safety Joint
Assembly Drawing
103465 07
Status: Approved

B.5



ITEM NO.	PART NUMBER	Revision	DESCRIPTION	Material	QTY.
1	103473	03	Top Sub	AISI 4140 125 ksi	1
2	103463	04	Mandrel BPSJ	AISI 4140 125 ksi	1
3	103472	04	Tension Sub	AISI 4140 125 ksi	1
4	103583	02	Blank Shear Ring, BPSJ	2.0975 (CuAl10Ni5Fe5)	1
5	103530	03	Bearing Ring	AISI 4140 125 ksi	1
6	103471	05	Compensating Piston	AISI 4140 125 ksi	1
7	103484	02	Fill Plug	AISI 4140 125 ksi	1
8	103479	02	[A9569-2] Fike Rupture Disk, PAD-I 15500psi @ 350degF	17-4 PH	1
9	103462	05	Housing, BPSJ	AISI 4140 125 ksi	1
10	103466	02	Torque Sub	AISI 4140 125 ksi	1
11	103477	04	Torque Lug	AISI 4140 125 ksi	5
12	104074	01	Release Lug, BPSJ	AISI 4140 125 ksi	3
13	103482	02	[PHFX0515400B Rev 2A] Pressure-relief valve, 10000psi, 0.281" dia	17-4 PH	1
14	103464	02	Bottom Sub	AISI 4140 125 ksi	1
15	104075		M5 x 0.8 Thread-Locking Shoulder Screw	Alloy Steel	3
16	103529		M8 x 1.25 x 12 Alloy Steel Cup-Point Set Screw	Carbon Steel 10.9	2
17	101959		M8 x 8 - DIN 916 Hexagon Socket Set Screws With Cup Point	Carbon Steel 10.9	2
18	103740		M10 x 1.5 x 12 Slotted Brass Flat-Tip Shear Screw - C675 Manganese Bronze	Manganese Bronze	6
19	101025		O-ring 82.14 X 3.53	FKM-75	1
20	102533		O-ring 78.97 X 3.53	FKM-75	2
21	103584		O-ring 101.19 X 3.53	FKM-75	3
21	103534		BUR 108.9 X 103.3 X 1,0 - Concave - Split	Polyetheretherketone (PEEK)	6
22	103585		O-ring 10.82 X 1.78	FKM-75	2
24	103535		BUR 85.1 X 79.5 X 1,0 - Concave	Polyetheretherketone (PEEK)	4
25	103536		BUR 88.2 X 82.6 X 1,0 - Concave	Polyetheretherketone (PEEK)	2

entech

End connections:	3-1/2 IF	Burst pressure (psi):	15000
Validation standard:	ISO 14998 V6	Collapse pressure (psi):	15000
Temperature rating (deg f):	350	Max tension (1000xdaN):	133446
Max downhole prssure (psi):	15000	Max compression (1000xdaN):	133446

Project Name: NPD - Below Packer Safety Joint — Project No.: PRJ-10048

Changed Date	Changed By	Approved Date	Approved By	Description	Revision
		2022-02-16	JTT	ECO0345	07
2022-01-05	KL	2022-01-05	KL	ECO0345	06
2021-11-05	JTT	2021-11-05	JTT	ECO265	05

Designed Date	Designed By	Approved Date	Approved By	Sheet Size	Product Line
2021-06-02	JS	2021-07-21	KL	A3	BPSJ

Weight	Metallics	Elastomers	Scale	Nominal Diameter
146.08	AISI 4140 125 ksi	FKM-75	1:20	3 ½"

European Projection

Below Packer Safety Joint Assembly Drawing

Document No. 103465 — Revision 07

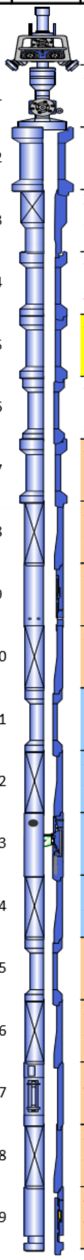
Status: Approved

C.1

Schlumberger String Diagram

Client	Well	Field	Rig	Date	WebSDP Number
Shell	TBD	TBD	TBD	27-Jul-22	001
Run #	**Temperature**	**Interval**	**Mud Weight**	**Mud Type**	**Max. Deviation**
1	200 DegF	19900-20000	10.00 lb/gl	CaCl	45

7-5/8" 39# Generic TCP BHA Draft



#	Tool	Description	Tensile Rating Klb	Working Pressure psi	Diameter OD in.	Diameter ID in.	Threads Top	Threads Bottom	Length feet	Depth Top feet	Depth Bottom feet
1		Side Entry Sub w/TIWs **SES**	1,500	15,000	8.00	3.06	5-7/8' DP Box	5-7/8' DP Pin	12.39	-12.39	0.00
2		5-7/8" Drill Pipe **Drill Pipe**			5.88	4.88	5-7/8' DP Box	5-7/8' DP Pin	11852.29	0.00	11852.29
3		X-Over **X-Over**			5.88	3.50	5-7/8' DP Box	4-1/2" DP Pin	3.50	11852.29	11855.79
4		4-1/2" Drill Pipe **Drill Pipe** TOL at XXXXX'			4.50	3.25	4-1/2" DP Box	4-1/2" DP Pin	7700.00	11855.79	19555.79
5		4-1/2" Drill Pipe **Pup Joint** Rig Provided			4.50	3.25	4-1/2" DP Box	4-1/2" DP Pin	10.00	19555.79	19565.79
6		4-1/2" Drill Pipe **Drill Pipe** Stand 1			4.00	2.88	4-1/2" DP Box	4-1/2" DP Pin	93.00	19565.79	19658.79
7		4-1/2" Drill Pipe **Handling Pup**			4.50	3.25	4-1/2" DP Box	4-1/2" DP Pin	8.00	19658.79	19666.79
8		X-Over **X-Over**			5.00	2.56	4-1/2" DP Box	3 1/2" IF Pin	2.05	19666.79	19668.84
9		Single Shot Hydrostatic Reversing **SHRV-FEA** PapL=XXXXpsi PapH=XXXXpsi	400	15,000	5.00	2.25	3 1/2" IF Box	3 1/2" IF Pin	4.44	19668.84	19673.28
10		Saver Sub **Saver Sub**			4.88	2.50	3 1/2" IF Box	3-1/2 IF Pin	2.00	19673.28	19675.28
11		3 1/2" 13.3# S-135 Pup Joint **3 1/2" IF Pup** Handling Pup	488	15,000	3.50	2.56	3-1/2 IF Box	3-1/2 IF Pin	8.00	19675.28	19683.28
12		X-Over **X-Over**	344	15,000	4.80	2.69	3-1/2 IF Box	3-1/2 PH6 Pin	1.50	19683.28	19684.78
13		IRIS Dual Valve **IRDV-AB** PapL=XXXXpsi PapH=XXXXpsi	320	15,000	5.00	2.25	3-1/2 PH6 Box	3-1/2 PH6 Pin	20.00	19684.78	19704.78
14		Cross over reducer **X-Over**	344	15,000	4.80	2.69	3-1/2 PH6 Box	3 1/2" IF Pin	1.09	19704.78	19705.87
15		3 1/2" 13.3# Pup Joint **Drill Pipe**			3.50	2.56	3 1/2" IF Box	3 1/2" IF Pin	7.00	19705.87	19712.87
16		X-Over **X-Over**			4.75	2.44	3 1/2" IF Box	3 1/2" PH6 Pin	2.00	19712.87	19714.87
17		Gauge Carrier **TDRC-DA**	350	15,000	5.00	2.25	3 1/2" PH6 Box	3 1/2" PH6 Pin	5.38	19714.87	19720.25
18		X-Over **X-Over**			4.75	2.44	3 1/2" PH6 Box	3 1/2" IF Pin	2.00	19720.25	19722.25
19		JAR **JAR-FEA**	350	15,000	5.00	2.25	3 1/2" IF Box	3 1/2" IF Pin	8.50	19722.25	19730.75

Client Representative:	Schlumberger Representative:	Page	Rev Nbr: 21	TPS/DST/SDP - Rev-6.4
Hypercare	Ray Verges Jr	1	27-Jul-22 15:23	

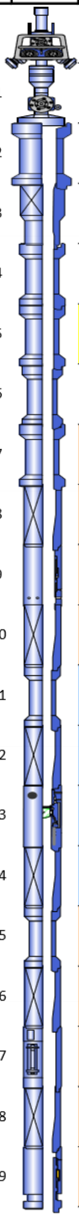
C.2

Schlumberger String Diagram

Client	Well	Field	Rig	Date	WebSDP Number
Shell	TBD	TBD	TBD	27-Jul-22	001

Run #	Temperature	Interval	Mud Weight	Mud Type	Max. Deviation
1	200 DegF	19900-20000	10.00 lb/gl	CaCl	45

7-5/8" 39# Generic TCP BHA Draft



#	Description	Tensile Rating (Klb)	Working Pressure (psi)	Diameter OD (in.)	Diameter ID (in.)	Threads Top	Threads Bottom	Length (feet)	Depth Top (feet)	Depth Bottom (feet)
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14	Cross over reducer **X-Over**	344	15,000	4.80	2.69	3-1/2 PH6 Box	3 1/2" IF Pin	1.09	19704.78	19705.87
15	3 1/2" 13.3# Pup Joint **Drill Pipe**			3.50	2.56	3 1/2" IF Box	3 1/2" IF Pin	7.00	19705.87	19712.87
16	X-Over **X-Over**			4.75	2.44	3 1/2" IF Box	3 1/2" PH6 Pin	2.00	19712.87	19714.87
17	Gauge Carrier **TDRC-DA**	350	15,000	5.00	2.25	3 1/2" PH6 Box	3 1/2" PH6 Pin	5.38	19714.87	19720.25
18	X-Over **X-Over**			4.75	2.44	3 1/2" PH6 Box	3 1/2" IF Pin	2.00	19720.25	19722.25
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Client Representative:	Schlumberger Representative:	Page	Rev Nbr: 21	TPS/DST/SDP - Rev-6.4
Hypercare	Ray Verges Jr	1	27-Jul-22 15:23	

D.1

MARKET DRIVEN INNOVATION

entech

Entech Team US Inc
315 Lilac Street
Suite E
Houston TX 77009
United States

Quality Alert report: QA00366

Deformation and corrosion in normal use

Entech Responsible Email: anthony.kent@entechteam.com
Entech Approver: jan.tore.tveranger@entechteam.com
QA progress status: New

Vendor/Customer:

Vendor/Customer NCR REF:

Place and date:

Location: Houston
Date created: 02/22/2023
Due Date: 02/24/2023

Product/subject information:

Finding type: Opportunity for improvement
Product: [103465-07] Below Packer Safety Joint
Lot/Serial no:
Entech Purchase Order #:

Description:
Gun shock is causing the BPSJ rupture disk to burst and resulting in the tool stroking open due to gun weight. When the tool strokes open, two issues have been identified that may adversely affect tool reliability and durability:

- Mandrel seal surface is exposed to wellbore fluids and pitting is starting to occur.
- The torque profile of the Compensating Piston is being impacted by the same on the Torque Sub, resulting in deformation at point of contact if the torque profiles are not perfectly aligned.

Two BPSJs have been returned to Entech for inspection and reliability engineering improvements. Attached photos of any defects observed during inspection.

Root cause analysis:
tbd

Corrective Action:
- Pitting - appears relatively minor and should not affect tool ratings or specifications; however, a new surface treatment should be applied that will increase the usable life of the mandrel by protecting the seal surface. Current coating is manganese phosphate.
ACTION: Bead blast mandrels and treat using QPQ process. QPQ is harder, more durable and corrosion resistant.
-

Preventive action:
tbd

entech

E.1

Product test report

Below Packer Safety Joint

March 9, 2023

Entech CTO	Jan Tore Tveranger
Entech Project Manager	Margrete Knarvik Yasmin Pourshahmiri Marie Gørbitz

Document ID	HVL vår2023
Project Title	Product test report, Below Packer Safety Joint
Author	HVL-TEAM

Rev	Date	Description	Originator	Approver
1	09.03.2023			

Contents

Test Personnel

Test supervisor: Jan Tore Tveranger

Test engineer: Margrete Knarvik, Yasmin Pourshahmiri and Marie Gørbitz

Introduction

The primary objective of the Below Packer Safety Joint is to function as a safety guard. One of the key safety features of this joint is its ability to give a shock or a yank to the string as it yields, thereby loosening the string.

Mandrel BPSJ - transfer energy to separating pressure zones inside the barrel.

Scope of test

1. To determine the rate of corrosion of sample under the specified conditions and the different well fluids.
2. To provide a basis for deciding protection coatings or treatments.
3. To identify any corrosion mechanisms that may be present and determine their impact on the corrosion behavior.
4. The test conditions will not replicate the same level of pressure experienced during application, which could potentially result in deviations from the expected outcomes.

Technical data / test parameters:

Fluid types:	1. KCL Brine 5% 1.03 SG potassium chloride 2. CaCl2 Brine 1.3 SG calcium chloride 3. CaBr2 Brine 1.7 SG Calium Bromide
Mandrel BPSJ:	Three test pieces of material for the component.
Material:	AISI 4140
Test pressure:	Ambient pressure
Test time:	5 Weeks
Temperature:	Ambient temperature
Inspection interval:	At set dates
Coating:	Manganese Phosphate

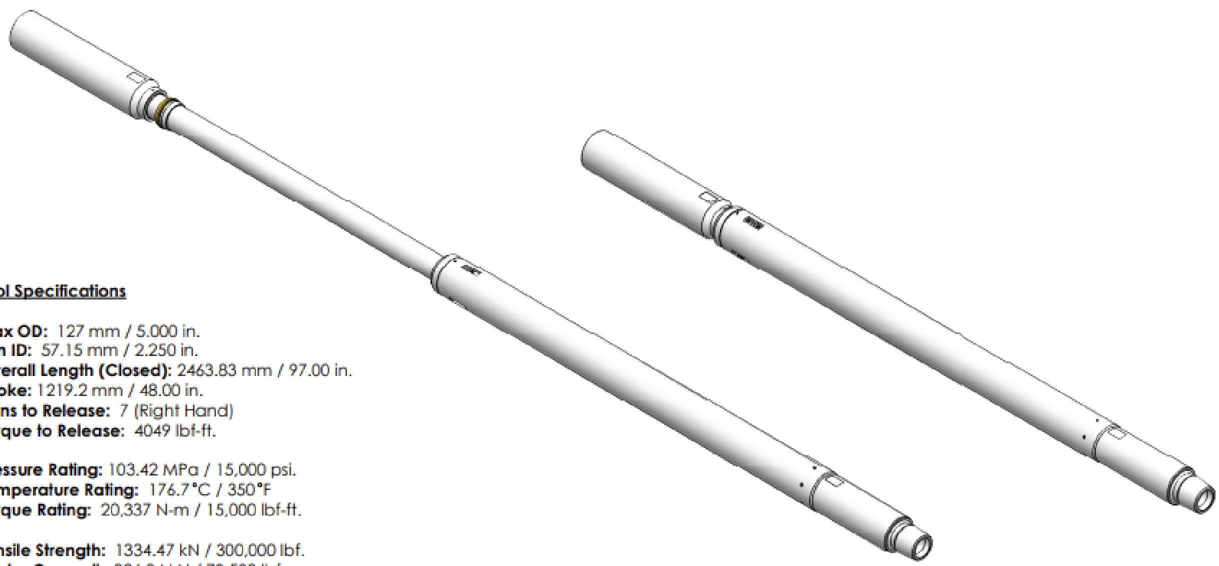
List of equipment

Item	Description	Quantity
1	Test container – low pressure	3
2	Test pieces	3
3	Test fluids one (Issued by client)	Liquid level completely covers the test piece
4	Test fluids two (Issued by client)	Liquid level completely covers the test piece
5	Test fluids three (Issued by client)	Liquid level completely covers the test piece

Mandrel BPSJ

entech BPSJ

Right-Hand Release, Below Packer Safety Joint



Tool Specifications

Max OD: 127 mm / 5.000 in.
Min ID: 57.15 mm / 2.250 in.
Overall Length (Closed): 2463.83 mm / 97.00 in.
Stroke: 1219.2 mm / 48.00 in.
Turns to Release: 7 (Right Hand)
Torque to Release: 4049 lbf-ft.

Pressure Rating: 103.42 MPa / 15,000 psi.
Temperature Rating: 176.7°C / 350°F
Torque Rating: 20,337 N-m / 15,000 lbf-ft.

Tensile Strength: 1334.47 kN / 300,000 lbf.
Stroke Overpull: 326.94 kN / 73,500 lbf.
Shear Ring Overpull:

- 222.41 kN / 50,000 lbf.
- 333.62kN / 75,000 lbf.
- 444.82 kN / 100,000 lbf.

Notes:

1. Activating tool with more than 100,000 lbf. tension or exceeding 10,000 lbf. down weight once actived will override hydraulic check and cause tool to act as a slip joint with 48" of free stroke.
2. Tool must be stroked full open to release.
3. Max tensile rating is with no differential pressure. For use in closed systems, refer to operating manual for differential pressure limitations.

entech

End connections:	3-1/2 IF	Burst pressure (psi):	15000
Validation standard:	ISO 14998 V6	Collapse pressure (psi):	15000
Temperature rating (deg f):	350	Max tension (1000xdaN):	133446
Max downhole pressure (psi):	15000	Max compression (1000xdaN):	133446

Project Name	NPD - Below Packer Safety Joint	Project No.	PRJ-10048

Changed Date	Changed By	Approved Date	Approved By	Description	Revision
		2022-02-16	JTT	ECO0345	07
2022-01-05	KL	2022-01-05	KL	ECO0345	06
2021-11-05	JTT	2021-11-05	JTT	ECO265	05

Designed Date	Designed By	Approved Date	Approved By	Sheet Size	Product Line	European Projection
2021-06-02	JS	2021-07-21	KL	A3	BPSJ	

Weight	Metallics	Elastomers	Scale	Nominal Diameter
146.08	AISI 4140 125 ksi	FKM-75	1:4	3 ½"

Below Packer Safety Joint
Assembly Drawing

Document No. 103465 Revision 07

Status: Approved

Test procedural checklist

Test day 1 (March 9) - Preparation

Test step	Description	Date / sign
1	Obtain three samples of the metal piece.	
2	Take pictures of the samples, both on the inside and outside, for comparison with later pictures.	
3	Obtain three containers for each liquid being tested.	
4	Label each sample with a unique identifier (e.g., Sample #1, Sample #2, Sample #3).	
5	Pour each liquid into a separate container.	
6	Place each sample in a separate container of one of the liquids.	
7	Close each container with an airtight lid.	

Test day 2 (March 31) - Observation

Test step	Description	Date / sign
1	Remove the samples from the containers.	
2	Take a picture each sample	
4	Examine each sample for any signs of corrosion, rust, or other damage.	
5	Record any observations.	

Test day 2 (March 31) - Preparation

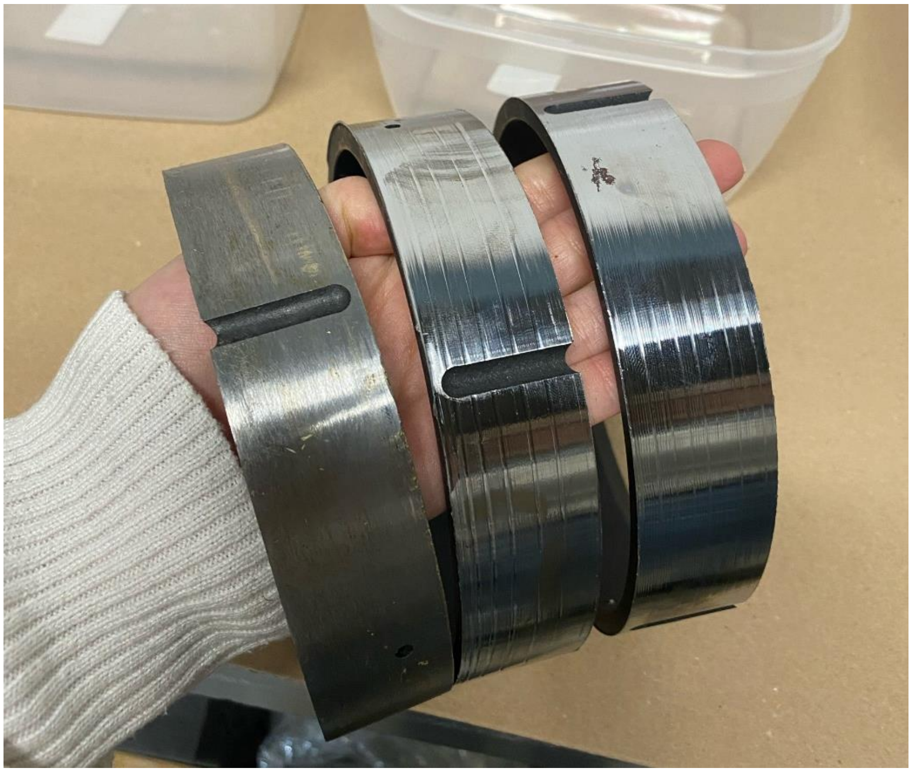
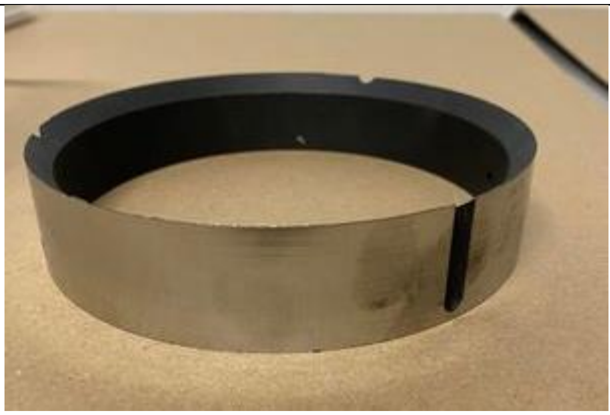
Test step	Description	Date / sign
1	Place each sample back in the same container of liquid as before.	
2	Close each container with an airtight lid.	
3	Tilt each container so that part of the sample is in the air.	
4	Close each container with an airtight lid.	

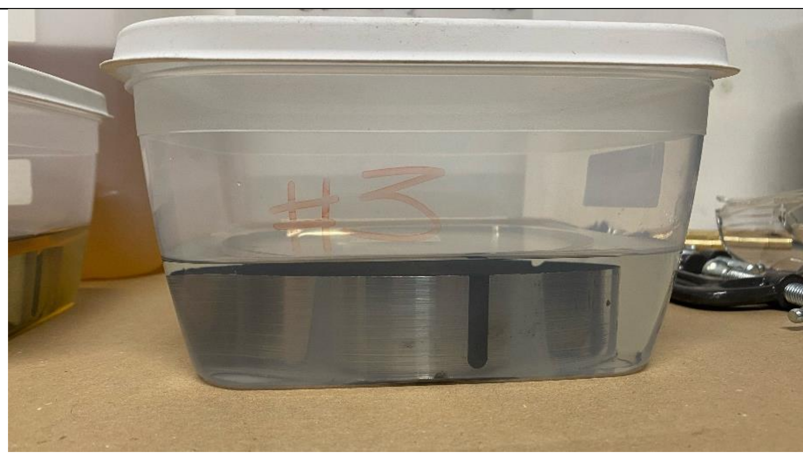
Test day 3 (April 14) - Observation

Test step	Description	Date / sign
1	Remove the samples from the containers.	
2	Take a picture	
3	Examine each sample for any signs of corrosion, rust, or other damage.	
4	Record any observations.	

Pictures

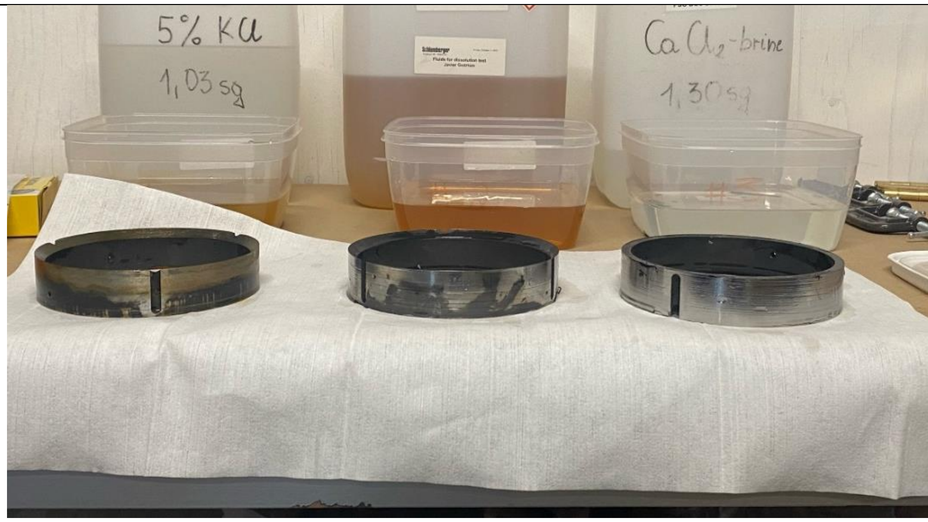
Photos: Test day 1 (March 9) - Preparation

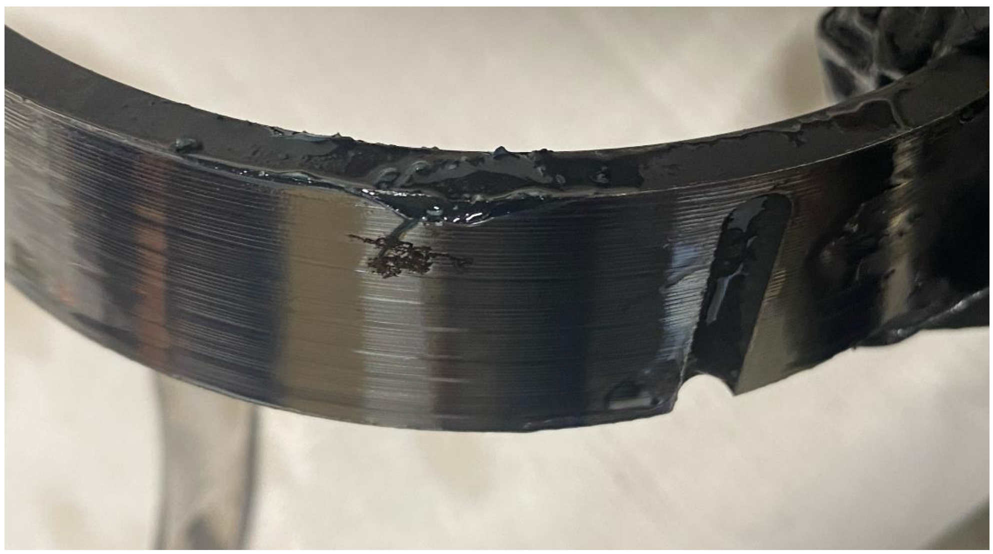
Description	**Photos**
Obtain three samples of the metal piece.	
Take pictures of the samples, both on the inside and outside, for comparison with later pictures.	

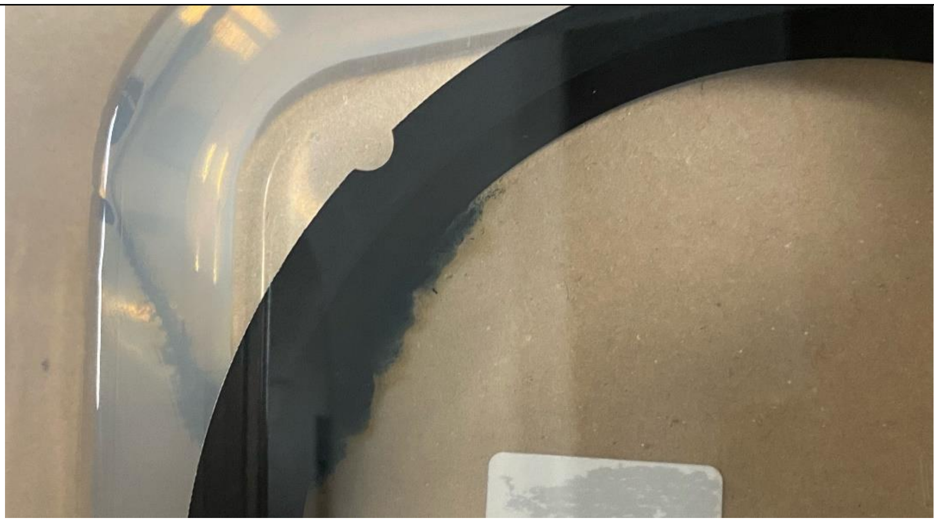
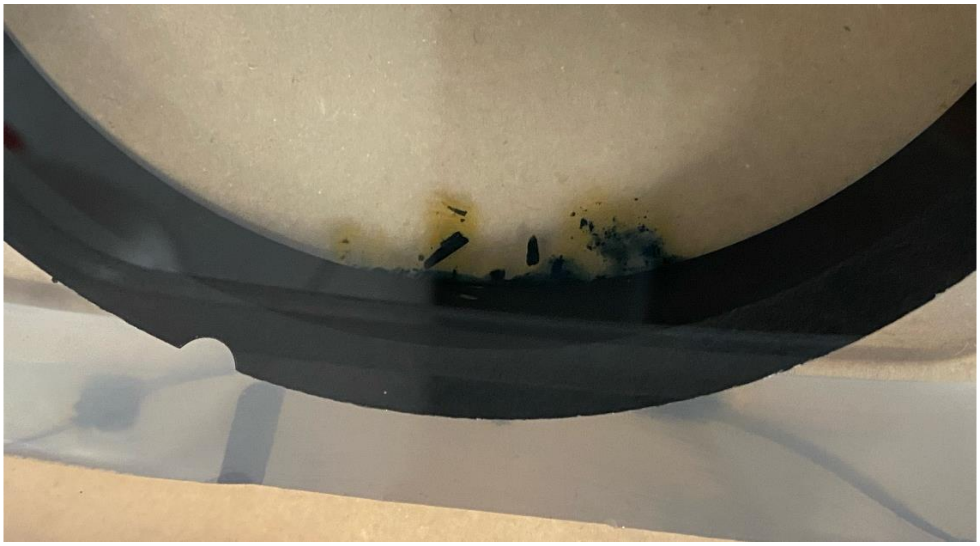
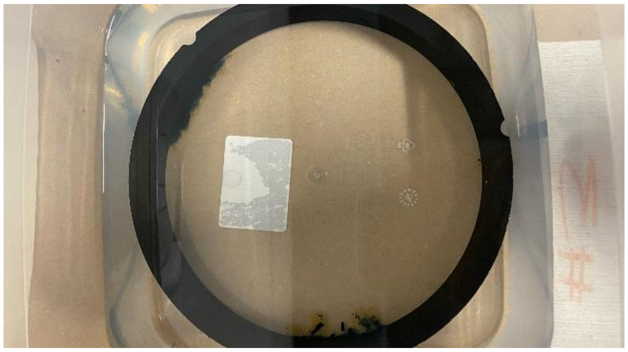
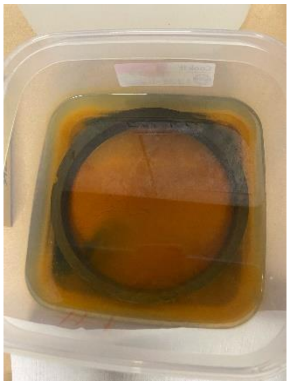
<table>
<tr>
<td>Obtain three containers for each liquid being tested.</td>
<td>
</td>
</tr>
<tr>
<td>Label each sample with a unique identifier (e.g., Sample #1, Sample #2, Sample #3).</td>
<td>
</td>
</tr>
</table>

<table>
<tr><td>Place each sample in a separate container of one of the liquids.</td><td></td></tr>
<tr><td>Pour each liquid into a separate container.</td><td rowspan="2">
</td></tr>
<tr><td>Close each container with an airtight lid.</td></tr>
</table>

Photos: Test day 2 (March 31) - Observation

<table>
<tr><th>Description</th><th>Photos</th></tr>
<tr><td>Remove the samples from the containers.</td><td>
</td></tr>
<tr><td>Take a picture of each sample</td><td rowspan="2"></td></tr>
<tr><td>Examine each sample for any signs of corrosion, rust, or other damage.</td></tr>
</table>



Record any observations.	   

Photos: Test day 2 (March 31) - Preparation

Description	Photos
Place each sample back in the same container of liquid as before.	
Close each container with an airtight lid.	
Tilt each container so that part of the sample is in the air.	
Close each container with an airtight lid.	

Photos: Test day 3 (April 14) - Observation

Description	Photos
Remove the samples from the containers.	 
Take pictures	
Examine each sample for any signs of corrosion, rust, or other damage.	
Record any observations.	 

F.1

Level	File Name	Number	Qty	Description	Revision	Material	Type
7	103479.sldprt	103479	1	[A9569-2] Fike Rupture Disk, PAD-I 15500psi @ 350degF	02	17-4 PH	Metall
23	103482.sldprt	103482	1	[PHFX0515400B Rev 2A] Pressure-relief valve, 10000psi, 0.281" dia	02	17-4 PH	Metall
13	103583.sldprt	103583	1	Blank Shear Ring, BPSJ	02	2.0975 (CuAl10Ni5Fe5)	Metall
1	103464.sldprt	103464	1	Bottom Sub	02	AISI 4140 125 ksi	Metall
2	103484.sldprt	103484	1	Fill Plug	02	AISI 4140 125 ksi	Metall
4	104074.sldprt	104074	3	Release Lug, BPSJ	01	AISI 4140 125 ksi	Metall
6	103477.sldprt	103477	5	Torque Lug	04	AISI 4140 125 ksi	Metall
8	103471.sldprt	103471	1	Compensating Piston	05	AISI 4140 125 ksi	Metall
10	103463.sldprt	103463	1	Mandrel BPSJ	04	AISI 4140 125 ksi	Metall
15	103473.sldprt	103473	1	Top Sub	03	AISI 4140 125 ksi	Metall
17	103466.sldprt	103466	1	Torque Sub	02	AISI 4140 125 ksi	Metall
19	103462.sldprt	103462	1	Housing, BPSJ	05	AISI 4140 125 ksi	Metall
22	103530.sldprt	103530	1	Bearing Ring	03	AISI 4140 125 ksi	Metall
24	103472.sldprt	103472	1	Tension Sub	04	AISI 4140 125 ksi	Metall
16	104075.sldprt	104075	3	M5 x 0.8 Thread-Locking Shoulder Screw		Alloy Steel	Metall
18	101959.SLDPRT	101959	2	M8 x 8 - DIN 916 Hexagon Socket Set Screws With Cup Point		Carbon Steel 10.9	Metall
25	103529.sldprt	103529	2	M8 x 1.25 x 12 Alloy Steel Cup-Point Set Screw		Carbon Steel 10.9	Metall
5	101025.sldprt	101025	1	O-ring 82.14 X 3.53		FKM-75	Pol
12	103584.sldprt	103584	3			FKM-75	Pol
14	103585.sldprt	103585	2	O-ring 10.82 X 1.78		FKM-75	Pol
21	102533.sldprt	102533	2	O-ring 78.97 X 3.53		FKM-75	Pol
9	103740.sldprt	103740	6	M10 x 1.5 x 12 Slotted Brass Flat-Tip Shear Screw - C675 Manganese Bronze		Manganese Bronze	Metall
3	103534.sldprt	103534	6	BUR 108.9 X 103.3 X 1,0 - Concave - Split		Polyetheretherketone (PEEK)	Pol
11	103536.sldprt	103536	2	BUR 88.2 X 82.6 X 1,0 - Concave		Polyetheretherketone (PEEK)	Pol
20	103535.sldprt	103535	4	BUR 85.1 X 79.5 X 1,0 - Concave		Polyetheretherketone (PEEK)	Pol

F.2

Level	Number	Description	Operational Modes	Function Failure Analysis		Critical Item Selection		
				Function	Failure	Functional Significant Item (FSI)	Maintenance cost significant item (MCSI)	Maintenance significant item (MSI)
1	103464	Bottom Sub	Operation: Normal	Secure components together	FCO: Failure to connect STD: Structural deficiency	Yes	Yes	**Yes**
			Operartion: Tension Release	Handel sett torque and tension load	FTF: Failure to function on demand			
			Operation: Disconnecting	Disconnet from the rest for BPSJ	FTD: failure to disconnect			
2	103484	Fill Plug	Installed	Contain hydraulic fluid	LCP: Leakage in closed position	No	No	No
			Uninstalled	Refill hydraulic fluid	FTO: Failure to open on demand FTC: Failure to close on demand			
4	104074	Release Lug, BPSJ	All modes	Avoid movement in axial direction for housing	STD: Structural deficiency FTF: Failure to function on demand	No	No	No
6	103477	Torque Lug	All modes	Prevent movement in all directions	FCD: failure to disconnect	No	No	No
7	103479	[A9569-2] Fike Rupture Disk, PAD-I 15500psi @ 350degF	All modes	Rupture when pressure exceeds set point	FTI: Failure to Function as intended	No	No	No
8	103471	Compensating Piston	Installed: Tension Release	Provide a seal and slide freely in axial direction	INL: Internal leakage STD: Structural deficiency	Yes	Yes	**Yes**
9	103740	M10 x 1.5 x 12 Slotted Brass Flat-Tip Shear Screw - C675 Manganese Bronze	Installed: Disconnect	To break at set screw torque	FTF: Failure to function on demand FCD: failure to disconnect	Yes	No	**Yes**
10	103463	Mandrel BPSJ	Installed: Tension Release	To separate the pressure zones inside the housing	STD: Structural deficiency FTO: Failure to open on demand	Yes	Yes	**Yes**
13	103583	Blank Shear Ring, BPSJ	Installed: Tension Release	Provide a mechanical weak point that is designed to break or "shear" at a specific pressure or load To break at sett shear load	FTF: Failure to function on demand STD: Structural deficiency	Yes	No	**Yes**
15	103473	Top Sub	All modes	Connect to the BHA (#27 drill pipe) Secure components together	FCO: Failure to connect to the BHA (#27 drill pipe) FCO: Failure to connect STD: Structural deficiency	No	No	No
16	104075	Thread-Locking Shoulder Screw	All modes	Secure components together	FCO: Failure to connect	No	No	No
17	103466	Torque Sub	Installed: Tension Release	Handle impact	STD: Structural deficiency	Yes	Yes	**Yes**
18	101959	M8 x 8 - DIN 916 Hexagon Socket Set Screws With Cup Point	All modes	Secure components together and prevent movement	FCO: Failure to connect (components together)	No	No	No
19	103462	Housing, BPSJ	All modes	Protective exterior of the structural elements	Unable to provide protection to the structural elements STD: Structural deficiency	No	No	No
22	103530	Bearing Ring	Installed: Tension Release		STD: Structural deficiency	No	No	No
23	103482	[PHFX0515400B Rev 2A] Pressure-relief valve, 10000psi, 0.281" dia	Installed: Tension Release	Open at design set pressure	FTO: Failure to open on demand LCP: Leakage in cosed position	No	No	No
24	103472	Tension Sub	All modes	Provides tension surfes for Blank Shear Ring	STD: Structural deficiency	No	No	No
25	103529	M8 x 1.25 x 12 Alloy Steel Cup-Point Set S	All modes	Secure components together	FCO: Failure to connect (components together)	No	No	No

F.3

		Consequence of Failure				
		A - Slight	B - Minor	C - Moderate	D - Major	E - Massive
Likelihood of Failure	5 - Expected	2-Pass with Condition(s)	3 - Fail	3 - Fail	3 - Fail	3 - Fail
	4 - High	2-Pass with Condition(s)	2-Pass with Condition(s)	3 - Fail	3 - Fail	3 - Fail
	3 - Medium	1 - Pass	2-Pass with Condition(s)	2-Pass with Condition(s)	2-Pass with Condition(s)	3 - Fail
	2 - low	1 - Pass	1 - Pass	2-Pass with Condition(s)	2-Pass with Condition(s)	2-Pass with Condition(s)
	1 - Negligble	1 - Pass	1 - Pass	1 - Pass	1 - Pass	2-Pass with Condition(s)

F.4

Maintainable Item		**Bottom Sub**				
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operartion: Tension Release	Operation: Disconnecting	Transportation and Storage: Time between campaigns
Function Failure Analysis	**Function**	Secure components together	Secure components together	Handle predetermined torque and withstand tension load	Disconnect from the rest for BPSJ	Maintain component integrity
	Function Failure	Movement or a total separation at the point of attachment	Movement or a total separation at the point of attachment	Movement or a total separation at the point of attachment	Housing not releasing from the bottom sub	Component integrity compromised
	Vulnerability	Structural deficiency because of * material of construction * chamfering, fillet and rounding Connections because of * weak threads and screws * sealing	Structural deficiency because of * material of construction * chamfering, fillet and rounding * mud, debree buildup Connections because of * weak threads and screws * sealing	Structural deficiency because of * material of construction * chamfering, fillet and rounding * mud, debree buildup Connections because of * weak threads and screws * sealing	Structural deficiency because of * material of construction * chamfering, fillet and rounding Connections because of * weak threads and screws	Structural deficiency because of * material of construction * chamfering, fillet and rounding Connections because of * weak threads and screws * sealing
	Failure Effect	Release at connection points at unintended time	Release at unintended time	Release at unintended time	Non-release	Release at unintended time
Operational Attack	**Operational Hazard**	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention. Physical - Loss of sealing - leakage of hydraulic fluid	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical: unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.
	Operational Attack Mechanism	Mechanical - Deformation of components Physical - Loss of pressure and influx of well fluid	Mechanical - Deformation of components	Mechanical - Deformation of components	Mechanical - Deformation of components	Mechanical: deformation of components
Equipment Failure Profile	**Equipment Failure Cause**	* Design - Unsuitable material * Manufacturing - fabrication and assembly * Usage - Human error	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure
	Equipment Failure Mechanism	1.3 Clearance / alignment failure 1.4 Deformation 2.5 Breakage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage
	Equipment Failure Mode	FCO: Failure to connect	FTD: Failure to disconnect	FTD: Failure to disconnect	FTD: Failure to disconnect	FCO: Failure to connect
	Equipment Failure Characteristics	Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Accident		Deformation of equipment connection points and leakage.	FTD: The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.
Environmental Attack	**Environmental Threat**	Mechanical: deformation hinder the placement/setting of tool to the string.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.
	Environmental Attack Mechanism	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Mechanical: compromised mechanical properties of the BottumSub necessitate the redistribution of the workload to other components, resulting in the inability to achieve the intended function solely through the use of these components.	Mechanical: compromised mechanical properties of the BottumSub necessitate the redistribution of the workload to other components, resulting in the inability to achieve the intended function solely through the use of these components.	Mechanical: compromised mechanical properties of the BottumSub necessitate the redistribution of the workload to other components, resulting in the inability to achieve the intended function solely through the use of these components.	Mechanical: compromised mechanical properties of the BottumSub necessitate the redistribution of the workload to other components, resulting in the inability to achieve the intended function solely through the use of these components.
Incidence		Deformation of equipment limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.
Criticality Analysis	**Likelihood of Failure**	2 - Low	1 - Negligble	2 - Low	2 - Low	4 - High
	Consequence of Failure	B - Minor	D - Major	D - Major	D - Major	B - Minor
	Risk Class	1 - Pass	1 - Pass	2 - Pass with Condition(s)	2 - Pass with Condition(s)	2 - Pass with Condition(s)

F.5

Maintainable Item		**Mandrel**				
Operational Modes		Operation: Normal	Operation: Tension Release	Operation: Disconnecting	Retrieval: String from Well	Transportation and Storage: Time between campaigns
Function Failure Analysis	**Function**	To separate the pressure zones inside the housing	To separate the pressure zones inside the housing	Load-bearing element	Load-bearing element	Maintain component integrity
	Function Failure	Incorrect pressure in reservoirs	Incorrect pressure in reservoirs	Not strong or stable enough to withstand the loads or stresses	Not strong or stable enough to withstand the loads or stresses	Component integrity compromised
	Vulnerability	Structural deficiency because of * material of construction * chamfering, fillet and rounding Containment of fluid *pressure difference	Structural deficiency because of * material of construction * chamfering, fillet and rounding * mud, debree buildup Containment of fluid *pressure difference Dynamics because of * Linear motion of the cylinder through the aperture	Structural deficiency because of * material of construction * chamfering, fillet and rounding	Structural deficiency because of * material of construction * chamfering, fillet and rounding	Structural deficiency because of * material of construction * chamfering, fillet and rounding
	Failure Effect	Non-release	Non-release	Stops other components from performing their function	Stops other components from performing their function	Unable to perform its function during next job run
Operational Attack	**Operational Hazard**	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical - Forces applied to the component may exceed the planned degree of retention.	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.
	Operational Attack Mechanism	Mechanical - Deformation of components	Mechanical - Deformation of components	Mechanical - Deformation of components	Mechanical - Deformation of components	Mechanical - Deformation of components
Equipment Failure Profile	**Equipment Failure Cause**	* Design - Unsuitable material * Manufacturing - fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system	* Design - Unsuitable material * Manufacturing - Fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system	* Design - Unsuitable material * Manufacturing - Fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system	* Design - Unsuitable material * Manufacturing - Fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system	* Design - Unsuitable material * Manufacturing - Fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system
	Equipment Failure Mechanism	2.5 Breakage 2.6 Fatigue	2.5 Breakage 2.6 Fatigue	2.5 Breakage 2.6 Fatigue	2.5 Breakage 2.6 Fatigue	2.5 Breakage 2.6 Fatigue
	Equipment Failure Mode	FCO: Failure to connect	FTD: Failure to disconnect	FCO: Failure to connect	FCO: Failure to connect	FCO: Failure to connect
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Accident		High pressure differential within the chamber exerts a significant amount of force, which can cause the mandrel to become damaged	The absence of pressure results in the failure to execute the Tension Release	Application of torque forces can lead to damage of the mandrel	Application of forces related to uninstallment of the tool can lead to damage of the mandrel	Application of unexpected forces (mishandling) can lead to damage of the mandrel
Environmental Attack	**Environmental Threat**	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	Mechanical: hinder the intended functionality of the other components, thereby impeding their ability to execute their designated tasks.	More costly and time consuming maintenance / repair
	Environmental Attack Mechanism	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Mechanical: resulting in the inability to achieve the intended function of the BPSJ.	Longer lead times
Incidence		Failure of Operation Mode: Tension Release	Partial loss of equipment (bottom sub and all equipment below)	Partial loss of equipment (bottom sub and all equipment below)	Partial loss of equipment (bottom sub and all equipment below)	Delayed operation for campaign
Criticality Analysis	**Likelihood of Failure**	1 - Negligible	3 - Medium	1 - Negligible	1 - Negligible	5 - Expected
	Consequence of Failure	C - Moderate	D - Major	B - Minor	B - Minor	B - Minor
	Risk Class	1 - Pass	2 - Pass with Condition(s)	1 - Pass	1 - Pass	3 - Fail

F.6

Maintainable Item		Compensating Piston		
Operational Modes		Operation: Normal	Operation: Tension Release	Transportation and Storage: Time between campaigns
Function Failure Analysis	Function	* Provide a seal	* Provide a seal * Allow mandrel (hydraulic piston) to slide freely in axial direction * Handle impact without deformation	Maintain component integrity
	Function Failure	Lack of sealing	* Lack of sealing * Madrel is not able to slide freely	Component integrity compromised
	Vulnerability	Connections because of * weak threads and screws * sealing Structural deficiency because of * material of construction * chamfering, fillet and rounding	Connections because of * weak threads and crews * sealing * impact zone Structural deficiency because of * material of construction * chamfering, fillet and rounding	Connections because of * weak threads and crews * sealing Structural deficiency because of * material of construction * chamfering, fillet and rounding
	Failure Effect	Leak of hydralic fluid	* Leak of hydraulic fluid * No movement of mandrel	Unable to perform its function during next job run
Operational Attack	Operational Hazard	Physical - Loss of sealing - leakage of hydraulic fluid	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention. Physical - Loss of sealing - leakage of hydraulic fluid	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.
	Operational Attack Mechanism	Physical - Loss of pressure and influx of well fluid	Mechanical - Deformation of components Physical - Loss of pressure and influx of well fluid	Mechanical - Deformation of components
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material, * Manufacturing - fabrication and assambly	* Design - Unsuitable material, * Manufacturing - Fabrication and assembly * Usage - Unexpected event during impact	* Design - Unsuitable material, * Manufacturing - Fabrication and assambly
	Equipment Failure Mechanism	1.1 Leaking 2.6 Fatigue	1.1 Leaking 1.4 deformation 2.6 Fatigue	1.1 Leaking 2.6 Fatigue
	Equipment Failure Mode	STD: Structural deficiency	STD: Structural deficiency	STD: Structural deficiency
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Accident		Leak of hydraulic fluid	Deformation of equipment connection points and leakage of hydraulic fluid.	Application of unexpected forces (mishandling) can lead to damage of the compensating piston.
Environmental Attack	Environmental Threat	Lack of pressure	Physical: Misalignment	More costly and time consuming maintenance / repair
	Environmental Attack Mechanism	Insufficient amount of hydraulic fluid in resuar	Mechanical: deformation hinder the placement	Longer lead times
Incidence		Failure of Operation Mode: Tension Release	It inhibits functionality and additional tools	Delayed operation for campaign
Criticality Analysis	Likelihood of Failure	2 - Low	4 - High	1 - Negligble
	Consequence of Failure	B - Minor	D - Major	B - Minor
	Risk Class	1 - Pass	3 - Fail	1 - Pass

F. 7

Maintainable Item		Blank Shear Ring			
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operartion: Tension Release	Retrieval: String from Well
Function Failure Analysis	Function	Prevent accidental setting or sealing of the packer during installation.	Provide a fail-safe mechanism in the event that the packer needs to be retrieved from the wellbore.	To break at a given load and activate the release process	Prevents the packer from disengaging or moving prematurely.
	Function Failure	Not strong or stable enough to withstand the loads or stresses	Not strong or stable enough to withstand the loads or stresses	Not shearing at the intended load	Not strong or stable enough to withstand the loads or stresses
	Vulnerability	Structural deficiency because of *Metallurgical properties in Shear off point	Structural deficiency because of *Metallurgical properties in Shear off point	Structural deficiency because of *Metallurgical properties in Shear off point	Structural deficiency because of *Metallurgical properties in Shear off point
	Failure Effect	Unwanted release	Unwanted release	Unwanted release	Unwanted release
Operational Attack	Operational Hazard	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical - Tension, shock loads, fatigue	Mechanical - Shearing is intact and mandrel does not move	Mechanical - Tension, shock loads, fatigue
	Operational Attack Mechanism	Mechanical - Break	Mechanical - Break	Mechanical - No Break	Mechanical - Break
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material * Manufacturing - Fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system	* Design - Unsuitable material * Manufacturing - fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system	* Design - Unsuitable material * Manufacturing - Fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system	* Design - Unsuitable material * Manufacturing - Fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system
	Equipment Failure Mechanism	2.5 Breakage	2.5 Breakage	2.5 Breakage	2.5 Breakage
	Equipment Failure Mode	STD: Structural deficiency	STD: Structural deficiency	STD: Structural deficiency FTF: Failure to function on demand	STD: Structural deficiency
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Accident		Relase before intended	Relase before intended	Tensioin release mechanism fails to activate	Lack of capacity to handle the hydralic tension of tool string under retrieval
Environmental Attack	Environmental Threat	Mechanical: unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical: unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical: unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical: unexpected forces applied to the component may exceed the planned degree of retention.
	Environmental Attack Mechanism	Mechanical: Break	Mechanical: Break	Mechanical: No Break	Mechanical: Break
Incidence		Failure of Operation Mode: Tension Release	Failure of Operation Mode: Tension Release	Partial loss of equipment (bottom sub and all equipment below)	Partial loss of equipment (bottom sub and all equipment below)
Criticality Analysis	Likelihood of Failure	1 - Negligble	5 - Expected	1 - Negligble	2 - Low
	Consequence of Failure	B - Minor	D - Major	C - Moderate	B - Minor
	Risk Class	1 - Pass	3 - Fail	1 - Pass	1 - Pass

F.8

Maintainable Item		**Shear Screw**	
Operational Modes		Preparation: Installing in the String	Operation: Disconnecting
Function Failure Analysis	**Function**	Hold components together	Break/shear at predetermined torque load.
	Function Failure	Loose components	Failure to respond on signal/activation (e.g. failure to shear)
	Vulnerability	Structural deficiency because of *Metallurgical properties in Shear off points	Structural deficiency because of *Metallurgical properties in Shear off points
	Failure Effect	Loss of connection between housing and bottom sub.	Disconnection mechanism does not activate
Operational Attack	**Operational Hazard**	Mechanical - Tension, shock loads, fatigue	Mechanical - Set torque is insufficient
	Operational Attack Mechanism	Mechanical - Break	Mechanical - No Break
Equipment Failure Profile	**Equipment Failure Cause**	* Design - Unsuitable material * Manufacturing - Fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system	* Design - Unsuitable material * Manufacturing - Fabrication and assembly * Usage - An unforeseen incident has occurred in another area of the system
	Equipment Failure Mechanism	2.5 Breakage	2.5 Breakage
	Equipment Failure Mode	STD: Structural deficiency	STD: Structural deficiency FTF: Failure to function on demand
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Accident		Relase before intended	The release of housing form bottom sub does not occur
Environmental Attack	**Environmental Threat**	Mechanical: unexpected forces applied to the component may exceed the planned degree of retention.	Mechanical: unexpected forces applied to the component may exceed the planned degree of retention.
	Environmental Attack Mechanism	Mechanical: Break	Mechanical: No Break
Incidence		Partial loss of equipment	loss of equipment
Criticality Analysis	**Likelihood of Failure**	1 - Negligble	1 - Negligble
	Consequence of Failure	D - Major	D - Major
	Risk Class	1 - Pass	1 - Pass

F. 9

Maintainable Item		Torque Sub			
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operartion: Tension Release	Transportation and Storage: Time between campaigns
Function Failure Analysis	**Function**	Provide sealing	Provide sealing	* Handle impact * Provide a seal * Slide freely in axial direction	Maintain component integrity
	Function Failure	Leakage of hydraulic fluid	Leakage of hydraulic fluid	Unable to withstand load impact	Component integrity compromised
	Vulnerability	Connections because of * weak threads and screws * sealing Structural deficiency because of * material of construction * chamfering, fillet and rounding	Connections because of * weak threads and screws * sealing Structural deficiency because of * material of construction * chamfering, fillet and rounding	Connections because of * weak threads and screws * sealing Structural deficiency because of * material of construction * chamfering, fillet and rounding	Connections because of * weak threads and screws * sealing Structural deficiency because of * material of construction * chamfering, fillet and rounding
	Failure Effect	Not being able to create the necessary internal pressure	Not being able to create the necessary internal pressure	Deformation of lugs/teeth section	Unable to perform its function during next job run
Operational Attack	**Operational Hazard**	Physical - Loss of sealing - leakage of hydraulic fluid	Physical - Loss of sealing - leakage of hydraulic fluid	Mechanical - Hydraulic setting from rig lead to tension in the packer	Mechanical - Unexpected forces applied to the component may exceed the planned degree of retention.
	Operational Attack Mechanism	Physical - Loss of pressure and influx of well fluid	Physical - Loss of pressure and influx of well fluid	Mechanical - Tension in the packer may result rotation	Mechanical - Deformation of components
Equipment Failure Profile	**Equipment Failure Cause**	Usage - An unforeseen incident has occurred in another area of the system	Usage - An unforeseen incident has occurred in another area of the system	Usage - Unplanned rotation during installation	Usage - An unforeseen incident has occurred in another area of the system
	Equipment Failure Mechanism	1.1 Leakage	1.1 Leakage	1.3 Clearance / alignment failure 1.4 Deformation	2.5 Breakage
	Equipment Failure Mode	INL - Leakage	INL - Leakage	STD - Structural deficiency OTH - other; calibration error	STD: Structural deficiency
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden	Sudden, Aging, Gradual
Accident		Leak of hydralic fluid	Leak of hydralic fluid	Teeth misaligned on impact	Application of unexpected forces (mishandling) can lead to damage of the torque sub.
Environmental Attack	**Environmental Threat**	Lack of pressure	Lack of pressure	Mechanical - Deformed part may result in improper alignment	More costly and time consuming maintenance / repair
	Environmental Attack Mechanism	Insufficient amount of hydraulic fluid in resuar	Insufficient amount of hydraulic fluid in resuar	Mechanical - May result in tool displacement	Longer lead times
Incidence		Failure of Operation Mode: Tension Release	Failure of Operation Mode: Tension Release	Unable to perform function (shear) in a different operational mode	Delayed operation for campaign
Criticality Analysis	**Likelihood of Failure**	1 - Negligible	1 - Negligible	5 - Expected	1 - Negligible
	Consequence of Failure	B - Minor	D - Major	C - Moderate	B - Minor
	Risk Class	1 - Pass	1 - Pass	3 - Fail	1 - Pass

F. 10

Maintainable Item		Bottom Sub				
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operartion: Tension Release	Operation: Disconnecting	Transportation and Storage: Time between campaigns
Function Failure Analysis	Function	Secure components together	Secure components together	Handle predetermined torque and withstand tension load	Disconnect from the rest for BPSJ	Maintain component integrity
	Function Failure	Movement or a total separation at the point of attachment	Movement or a total separation at the point of attachment	Movement or a total separation at the point of attachment	Housing not releasing from the bottom sub	Component integrity compromised
	Vulnerability	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity, the thread are specifically exposed.	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load bearing and may be subjected to forces in excess of its capacity, the threads are specifically exposed. *Thermal: Loss of strength and composition due to high temperature variation.	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity, the threads are specifically exposed. *Thermal: Loss of strength and composition due to high temprature variation.	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity, the threads are specifically exposed. *Thermal: Loss of strength and composition due to high temprature variation.	*Chemical: The material can chemically react with substances in the system/environment. *Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity, the thread are specifically exposed.
	Failure Effect	Release at unintended time	Release at unintended time	Release at unintended time	Non-release	Release at unintended time
Environmental Attack	Environmental Threat	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation
	Environmental Attack Mechanism	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact *Thermal - Non-optimal mechanics of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure
	Equipment Failure Mechanism	2.2 Corrosion 2.5 Breakage	2.2 Corrosion 2.5 Breakage 2.6 Fatigue 5.3 Misc. External influence	2.2 Corrosion 2.5 Breakage 2.6 Fatigue 5.3 Misc. External influence	2.2 Corrosion 2.5 Breakage 2.6 Fatigue 5.3 Misc. External influence	2.2 Corrosion 2.5 Breakage
	Equipment Failure Mode	FCO: Failure to connect	FTD: Failure to disconnect	FTD: Failure to disconnect	FTD: Failure to disconnect	FCO: Failure to connect
	Equipment Failure Characteristics	Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Incidence		Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	FCO: Failure to connect
Operational Attack	Operational Hazard	* Mechanical - Corroded part may result in weak structure * Mechanical - Deformed part may result in improper securing	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure * Thermal - Temperature variations may lessen the materials structural integrity.	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure * Thermal - Temperature variations may lessen the materials structural integrity.	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure * Thermal - Temperature variations may lessen the materials structural integrity.	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure
	Operational Attack Mechanism	* Mechanical - Weak structure may result in breakage * Mechanical - Improper securing may result in disconnect	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage * Thermal - Compromised structural integrity resulting in fracture	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage * Thermal - Compromised structural integrity resulting in fracture	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage * Thermal - Compromised structural integrity resulting in fracture	Chemical - Corrosion may lead to material damage Mechanical - Weak structur may lead to breakage in not indented places
Accident		Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	The tool strings fail to ascend from the well	Tool strings restricted mobility, thereby limiting their operational effectiveness and potentially disconnecting from the lower equipment installed in the well, leading to a complete cessation of operations.
Criticality Analysis	Likelihood of Failure	3 - Medium	1 - Negligble	1 - Negligble	1 - Negligble	1 - Negligble
	Consequence of Failure	A - Slight	E - Massive	E - Massive	E - Massive	C - Moderate
	Risk Class	1 - Pass	2 - Pass with Condition(s)	2 - Pass with Condition(s)	2 - Pass with Condition(s)	1 - Pass

F. 11

Maintainable Item		Mandrel				
Operational Modes		Operation: Normal	Operation: Tension Release	Operation: Disconnecting	Retrieval: String from Well	Transportation and Storage: Time between campaigns
Function Failure Analysis	Function	To separate the pressure zones inside the housing	To separate the pressure zones inside the housing	Load-bearing element	Load-bearing element	Maintain component integrity
	Function Failure	Incorrect pressure in hydraulic fluid reservoirs	Incorrect pressure in hydraulic fluid reservoirs	Not strong or stable enough to withstand the loads or stresses	Not strong or stable enough to withstand the loads or stresses	Component integrity compromised
	Vulnerability	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strenght and composition due to high temperature variation.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temprature variation.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temprature variation.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.
	Failure Effect	Non-release	Non-release	Stops other components from performing their function	Stops other components from performing their function	Unable to perform its function during next job run
Environmental Attack	Environmental Threat	* Chemical - Environment (Chemical and brines) that can corrode *Mechanical - Tension, shock loads, fatigue *Therma - high temprature in relation to matrial compesiti	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving machines that lead to deformation	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation
	Environmental Attack Mechanism	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure
	Equipment Failure Mechanism	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage 2.6 Fatigue	2.2 Corrosion 2.5 Breakage 2.6 Fatigue
	Equipment Failure Mode	FCO: Failure to connect	FTD: Failure to disconnect	FCO: Failure to connect	FCO: Failure to connect	FCO: Failure to connect
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Incidence		The connection fails and the pressure zones is not intackt	The mandrel fail to slide out from housing	Loads over expected or design capacity resulting in breakage and cracking	Loads over expected or design capacity resulting in breakage and cracking	Integrity of the component is compromised for future use
Operational Attack	Operational Hazard	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure * Thermal - Temperature variations may lessen the materials structural integrity	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure * Thermal - Temperature variations may lessen the materials structural integrity	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure * Thermal - Temperature variations may lessen the materials structural integrity	* Chemical - Brines may corrode the component * Mechanical - Corroded part may result in weak structure	More costly and time consuming maintenance / repair
	Operational Attack Mechanism	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage * Thermal - Compromised structural integrity resulting in fracture	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage * Thermal - Compromised structural integrity resulting in fracture	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage * Thermal - Compromised structural integrity resulting in fracture	* Chemical - Corrosion may lead to material damage * Mechanical - Weak structure may lead to breakage	Longer lead times
Accident		Failure of Operation Mode: Tension Release	Partial loss of equipment (bottom sub and all equipment below)	Partial loss of equipment (bottom sub and all equipment below)	Partial loss of equipment (bottom sub and all equipment below)	Delayed operation
Criticality Analysis	Likelihood of Failure	1 - Negligble	1 - Negligble	1 - Negligble	1 - Negligble	5 - Expected
	Consequence of Failure	C - Moderate	D - Major	C - Moderate	C - Moderate	C - Moderate
	Risk Class	1 - Pass	1 - Pass	1 - Pass	1 - Pass	3 - Fail

F. 12

Maintainable Item		Compensating Piston			
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operation: Tension Release	Transportation and Storage: Time between campaigns
Function Failure Analysis	Function	Provide a seal	Provide a seal	* Provide a seal * Allow mandrel (hydraulic piston) to slide freely in axial direction * Handle impact without deformation	Maintain component integrity
	Function Failure	Lack of sealing	Lack of sealing	* Lack of sealing * Madrel is not able to slide freely	Component integrity compromised
	Vulnerability	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition do to high temperature variations.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temperature variations.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.
	Failure Effect	Leak of hydraulic fluid	Leak of hydralic fluid	* Leak of hydraulic fluid * No movement of mandrel	Unable to perform its function during next job run
Environmental Attack	Environmental Threat	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation	* Chemical - Environment (Chemical and brines) that can corrode *Mechanical - Tension, shock loads, fatigue *Therma - high temprature in relation to matrial compesiti	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation
	Environmental Attack Mechanism	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure
	Equipment Failure Mechanism	1.1 Leakage	1.1 Leakage	1.1 Leaking 1.4 Deformation 2.2 Corrosion	2.2 Corrosion 2.5 Breakage
	Equipment Failure Mode	INL - Leakage	INL: Leakage	INL: Leakage STD: Structural deficiency	STD: Structural deficiency
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Incidence		A lack of hydraulic fluid	A lack of hydraulic fluid	No tension release	Integrity of the component is compromised for future use
Operational Attack	Operational Hazard	Mechanical - Unsufficient amount of hydralic fluid	Mechanical - Insufficient amount of hydraulic fluid	* Mechanical - Insufficient amount of hydraulic fluid * Mechanical - Deformation of the teeth/lugs	More costly and time consuming maintenance / repair
	Operational Attack Mechanism	Mechanical - Not enough pressure buildup	Mechanical - Not enough pressure buildup	* Mechanical - Not enough pressure buildup * Mechanical - Deformation leading to material wear and tear	Longer lead times
Accident		Not releasing at a later operational mode	Not releasing at a later operational mode	Partial loss of equipment (bottom sub and all equipment below)	Delayed operation
Criticality Analysis	Likelihood of Failure	1 - Negligble	1 - Negligble	1 - Negligble	2 - Low
	Consequence of Failure	C - Moderate	C - Moderate	D - Major	D - Major
	Risk Class	1 - Pass	1 - Pass	1 - Pass	2 - Pass with Condition(s)

F. 13

Maintainable Item		Blank Shear Ring				
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operartion: Tension Release	Retrieval: String from Well	Transportation and Storage: Time between campaigns
Function Failure Analysis	Function	Prevent accidental setting or sealing of the packer during installation.	Provide a fail-safe mechanism in the event that the packer needs to be retrieved from the wellbore.	To break at a given load and activate the release process	Prevents the packer from disengaging or moving prematurely.	Maintain component integrity
	Function Failure	Not strong or stable enough to withstand the loads or stresses	Not strong or stable enough to withstand the loads or stresses	Not shearing at the intended load	* Not strong or stable enough to withstand the loads or stresses	Component integrity compromised
	Vulnerability	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temperature variations.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temperature variations.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.
	Failure Effect	Unwanted release	Unwanted release	Unwanted release	Unwanted release	Unable to perform its function during next job run
Environmental Attack	Environmental Threat	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation
	Environmental Attack Mechanism	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact *Terma - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure
	Equipment Failure Mechanism	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage	1.3 Clearance/alignment failure 2.2 Corrosion 2.5 Breakage
	Equipment Failure Mode	STD: Structural deficiency	STD: Structural deficiency	STD: Structural deficiency	STD: Structural deficiency	STD: Structural deficiency
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Incidence		Relase before intended	Relase before intended	Tensioin release mechanism fails to activate	Lack of capacity to handle the hydralic tension of tool string under retrieval	Integrity of the component is compromised for future use
Operational Attack	Operational Hazard	Mechanical - Ring breaks before signal activation	Mechanical - Ring breaks before signal activation	Mechanical - Ring does not break during signal activation	Mechanical - Loss of surrounding components	More costly and time consuming maintenance / repair
	Operational Attack Mechanism	Mechanical - shock loads	Mechanical - Shock loads	Mechanical - Manufacturing flaw resulting in failure to shear	Mechanical - Shock loads resulting in screws to shear	Longer lead times
Accident		Partial loss of equipment (bottom sub and all equipment below)	Partial loss of equipment (bottom sub and all equipment below)	Partial loss of equipment (bottom sub and all equipment below)	Retrieval of a tool causing unintended tension release	Delayed operation
Criticality Analysis	Likelihood of Failure	1 - Negligble	1 - Negligble	1 - Negligble	1 - Negligble	1 - Negligble
	Consequence of Failure	C - Moderate	C - Moderate	C - Moderate	E - Massive	C - Moderate
	Risk Class	1 - Pass	1 - Pass	1 - Pass	2 - Pass with Condition(s)	1 - Pass

F.14

Maintainable Item		Shear Screw					
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operation: Tension Release	Operation: Disconnecting	Retrieval: String from Well	Transportation and Storage: Time between campaigns
Function Failure Analysis	Function	Hold components together	Hold components together	Hold components together	Break/shear at predetermined torque load.	Not relevant if disconnection mechanism was activated. If not the case, the component function is to hold components together.	Maintain component integrity
	Function Failure	Loose components	Loose components	Loose components	Failure to respond on signal/activation (e.g. failure to shear)	Loose components	Component integrity compromised
	Vulnerability	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The components load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temperature variations.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temperature variations.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temperature variations.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the components in contact with people.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.
	Failure Effect	Loss of connection between housing and bottom sub.	Loss of connection between housing and bottom sub.	Loss of connection between housing and bottom sub.	Disconnection mechanism does not activate	Loss of connection between housing and bottom sub.	Unable to perform its function during next job run
Environmental Attack	Environmental Threat	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - high temprature in relation to matrial compesiti	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation
	Environmental Attack Mechanism	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture / breakage of parts due to impact
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure
	Equipment Failure Mechanism	1.3 Clearance/alignment failure 1.5 Looseness 2.2 Corrosion 2.5 Breakage	1.3 Clearance/alignment failure 1.5 Looseness 2.2 Corrosion 2.5 Breakage	1.3 Clearance/alignment failure 1.5 Looseness 2.2 Corrosion 2.5 Breakage	5.3 Miscellaneous external influences	1.3 Clearance/alignment failure 1.5 Looseness 2.2 Corrosion 2.5 Breakage	2.2 Corrosion 2.5 Breakage
	Equipment Failure Mode	STD: Structural deficiency	STD: Structural deficiency	STD: Structural deficiency	FTF: Failure to function on demand	STD: Structural deficiency	STD: Structural deficiency
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Incidence		Looseness - May result in deformation, fracture or breakage	Looseness - May result in deformation, fracture or breakage	Looseness - May result in deformation, fracture or breakage	Signal failure - Scews stay in tact	Looseness - May result in deformation, fracture or breakage	Integrity of the component is compromised for future use
Operational Attack	Operational Hazard	Mechanical - Screws break before signal activation	Mechanical - Screws break before signal activation	Mechanical - Screws break before signal activation	Mechanical - Screws don't break during signal activation	Mechanical - Loss of surrounding components	More costly and time consuming maintenance / repair
	Operational Attack Mechanism	Mechanical - Shock loads	Mechanical - Shock loads	Mechanical - Shock loads resulting in screws to shear	Mechanical - Manufacturing flaw resulting in failure to shear	Mechanical - Shock loads resulting in screws to shear	Longer lead times
Accident		Equipment located beneath the BSPJ is lost, requiring the removal of the string	Equipment located beneath the BSPJ is lost, requiring the removal of the string	Equipment located beneath the BSPJ is lost, requiring the removal of the string	Retrieval failed and complete loss of string equipment	Loss of equipment below BPSJ	Delayed operation
Criticality Analysis	Likelihood of Failure	1 - Negligble	1 - Negligble	1 - Negligble	1 - Negligble	1 - Negligble	1 - Negligble
	Consequence of Failure	C - Moderate	C - Moderate	C - Moderate	C - Moderate	C - Moderate	C - Moderate
	Risk Class	1 - Pass	1 - Pass	1 - Pass	1 - Pass	1 - Pass	1 - Pass

Maintainable Item		Torque Sub			
Operational Modes		Preparation: Installing in the String	Operation: Normal	Operartion: Tension Release	Transportation and Storage: Time between campaigns
Function Failure Analysis	Function	Provide sealing	Provide sealing	*Handle impact * Provide a seal * Slide freely in axial direction	Maintain component integrity
	Function Failure	Leakage of huydralic fluid	Leakage of huydralic fluid	Unable to withstand load impact	Component integrity compromised
	Vulnerability	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temperature variations.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: The component is load-bearing and may be subjected to forces in excess of its capacity. * Thermal: Loss of strength and composition due to high temperature variations.	* Chemical: The material can chemically react with substances in the system/environment. * Mechanical: During this operational mode, the component is in contact with people.
	Failure Effect	Not being able to create the necessary internal pressure	Not being able to create the necessary internal pressure	Deformation of lugs/teeth section	Unable to perform its function during next job run
Environmental Attack	Environmental Threat	* Chemical - Environment (moisture & salinity in air) that can corrode * Mechanical - Presence of humans and other moving parts that lead to deformation	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	* Chemical - Environment (Chemical and brines) that can corrode * Mechanical - Tension, shock loads, fatigue * Thermal - High temperature in relation to material composition	Not relevant
	Environmental Attack Mechanism	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	* Chemical - Environmental corrosion * Mechanical - Deformation of parts due to impact * Mechanical - Fracture/breakage of parts due to impact * Thermal - Non-optimal mechanism of the mechanical properties	Not relevant
Equipment Failure Profile	Equipment Failure Cause	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage (Aging) - Loosening and instability of supporting structure	* Design - Unsuitable material * Design - Unsuitable corrosion protection mechanisms * Usage - Human error * Usage (Aging) - Loosening and instability of supporting structure
	Equipment Failure Mechanism	1.1 Leakage	1.1 Leakage	1.4 Deformation	2.2 Corrosion 2.5 Breakage
	Equipment Failure Mode	INL - Leakage	INL - Leakage	STD - Structural deficiency	STD: Structural deficiency
	Equipment Failure Characteristics	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual	Sudden, Aging, Gradual
Incidence		Leak of hydraulic fluid	Leak of hydraulic fluid	Weaking of the structural component	Integrity of the component is compromised for future use
Operational Attack	Operational Hazard	Mechanical - Unsufficient amount of hydralic fluid	Mechanical - Unsufficient amount of hydralic fluid	Mechanical - Corroded part may result in weak structure	More costly and time consuming maintenance / repair
	Operational Attack Mechanism	Mechanical - Not enough pressure buildup	Mechanical - Not enough pressure buildup	Mechanical - Weak structure may result in breakage	Longer lead times
Accident		Not releasing at a later operational mode	Not releasing at a later operational mode	Not releasing at a later operational mode	Delayed operation
Criticality Analysis	Likelihood of Failure	1 - Negligble	1 - Negligble	3 - Medium	1 - Negligble
	Consequence of Failure	D - Major	D - Major	A - Slight	A - Slight
	Risk Class	1 - Pass	1 - Pass	1 - Pass	1 - Pass