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Maya Blaauw

Summary

Blow Out Preventer, often referred to as BOP, is an important tool in drilling operation in the Oil and Gas industry. It is also one of the most important tools to secure the safety of drilling operations. Once a BOP system failure occurs, it is necessary to perform maintenance of the BOP system, which will lead a certain downtime and millions of financial losses. A BOP system failure could also in worst case lead to a blow out, which could lead to catastrophic consequences beyond our ability to estimate, with huge financial, health and environmental and reputational losses. Thus, reliability research is necessary in the risk analysis of the BOP.

Reliability research includes reliability analysis and reliability calculation that both needs to be based on accurate history data. In this thesis, failure history and data are collected from many risks analysis reports and reliability research papers which are then further taken into a reliability risk analysis.

This thesis first introduces a BOP system and its structure, function and operation environment, which provides a basis for the establishment of reliability model. In order to prevent blowout incidents on offshore drilling rigs, it is important to ensure a reliable, safe and efficient operation of the BOP system. This paper introduces a combined method of FMECA method and bow-tie risk analysis model to analyse the causes and consequences of a BOP system failure. All possible failure modes of the BOP system and equipment are first defined, then the failure modes are sorted and analysed. The most harmful or serious failure modes is then determined.

For system failures modes with serious consequences, a bow-tie analysis model is implemented to find all the causes of failures including human factors. A summary is given to go over the five main failure reasons and is finally concluded with some further improvement suggestions.

Based on the structure and function of the BOP system, a reliability allocation model is established and simplified. By using the analytic hierarchy process, the reliability index of the system is allocated to each of the equipment. A fault tree analysis is used to complete the reliability prediction of the overall BOP system. According to the reliability prediction results, the preliminary design of the BOP system meets the MTBF requirements.

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1. Introduction

1.1. Background

The explosion on the drilling rig, Deepwater Horizon, often referred to as the Macondo accident, that happened in 2010 is one of the most known accidents in the oil and gas industry. It shows how a big accident in the industry affects not only the oil and gas industry, but other industries as well.
There were 11 killed and 17 injured as a result of the incident and the Gulf of Mexico was polluted for more than six months afterwards due to the oil spill. [1]

If the BOP system fails during deep-water drilling operations, they must be retrieved for maintenance which will cause significant economic losses. Blowout caused by equipment failure will bring disastrous consequences, and the losses are incalculable. Therefore, a reliability research is an important task in risk analysis and risk assessment of blowout preventer system used in deep-water operations.

In the past decades, several companies have made great technological progress in BOP design, including improvements in materials used, manufacturing, and testing. The operability, applicability, and reliability of BOP system have also greatly improved. [2]

Reliability research started in the middle of the last century. It is a discipline that studies the characteristics of system failures and how to avoid them. It was not discovered through experiments in a laboratory, neither derived from formulas, but developed through long-term research study from experiences and lessons learned after accidents. [3]

On a global perspective, reliability theory has gradually matured. During the development of the North Sea drilling operations in Norway, SINTEF have conducted several researches on the reliability of the underwater BOP control systems. This is based on deep-water drilling data, failure data, failure mode of the equipment, and evaluation the reliability of the equipment based on statistics and analytical results. [4]

1.2. Objectives

This thesis carries out a reliability analysis on deep-water BOP system, combine with two analytical methods. The main objectives of the thesis include:

(1) Introduce basic drilling and well contraction and the BOP system.
(2) Collection and sorting of historical failure data.
(3) Analyse BOP system reliability by FMECA method.
(4) Analyse BOP system reliability by Bow-Tie method.
(5) Reliability allocation and prediction based on reliability analysis results.

Failure mode effects and criticality analysis (FMECA) and Bow-Tie analysis (combination of FTA and ETA) are both common and effective methods for system reliability analysis. However, both methods have some certain limitations. For a complex system such as deep-water blowout preventer system, it is difficult to get good result by only using one simple analytical method.

This thesis will therefore carry out a combination of FMECA and a Bow-Tie analysis on a BOP system. Firstly, find out the failure mode of the BOP system and equipment through a FMECA analysis to determine the degree of hazard, and then find out the possible causes of the failures by a Bow-Tie analysis on these high-risk system failure modes.

Reliability allocation is an important part in system reliability research. It allocates the system's reliability to each equipment and components, according to the different structure and function of each of the equipment and component in the BOP system. Reliability allocation helps to implement the system reliability and provide foundation for reliability test and BOP system acceptance.

Reliability prediction is used to estimate the reliability of the BOP system under given operating conditions. It predicts the reliability of the BOP system based on the reliability of the units and components. Reliability of the BOP system can be calculated with a reliability prediction and can be used to check whether the BOP system meets the requirements.

1.3. Method

1.3.1. FMECA method

Failure mode effects and criticality analysis (FMECA) is a common method of reliability analysis. It analyses the potential failure modes of each component and unit in the system, their impact on system functions, and the severity of the consequences. The result from the analysis helps to propose possible improvement measures to improve the system reliability.

The FMECA method includes two aspects. The failure mode effects analysis (FMEA) and the criticality analysis (CA). The former analysis is qualitative, while the latter analysis is data based. FMECA method give more accurate result than the FMEA method, but when there is a leak of history data, FMEA analysis can be implement first, and CA analysis can be implemented when enough data is supplemented. FMECA method is widely used in many industries and fields. [5]

1.3.2. Bow-Tie method

Bow-Tie method is a combination of FTA (Fault tree analysis) and ETA (Event tree analysis). FTA method is an important method to evaluate the reliability and safety of complex systems. The FTA analysis helps to analyse various factors that may cause product failure, by drawing a logical block diagram (i.e., fault tree) would help to determine the cause of system failure and its various possible combinations. It is also possible to calculate of the probability of occurrence, which helps to determine corrective measures to improve the system reliability. ETA analysis is also a common method used in system reliability analysis. It originates from the decision tree analysis (DTA) and brings possible consequences from the initial event and identifies the hazard. This method expresses the logical relationship between a certain accident that may occur in the system and various causes leading to the accident, using a tree diagram. It uses qualitative and quantitative analysis of the event tree to determine the main reason of the occurrence and provides a reliable basis for safety measures.

The bow-Tie method combines the FTA on the left side and the ETA on the right side as a tie shape analysis to express the relationship of the top event, the causes of accidents and how it happened, consequences of the accidents and the measures to prevent further accidents. [6]

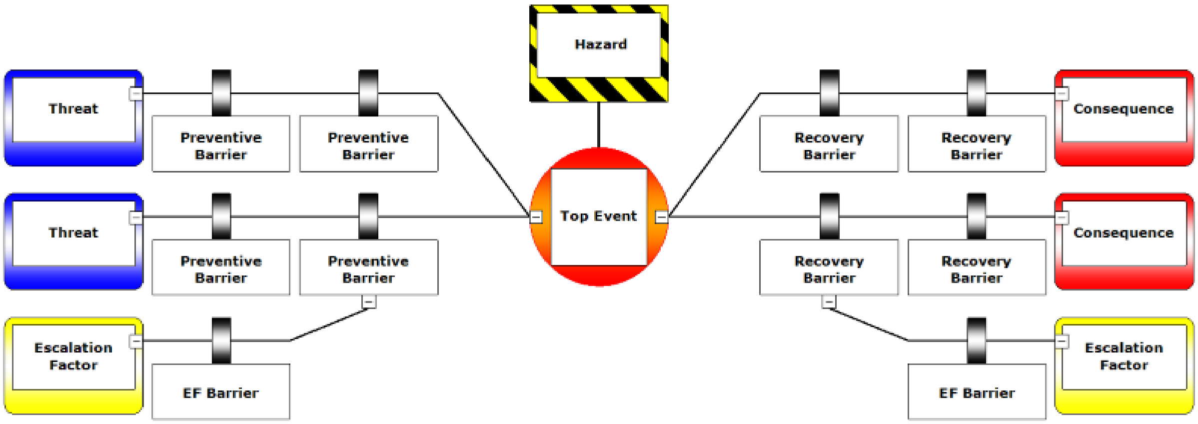

Figure 1: An example of a bowtie diagram.

1.4. Structure of the thesis

Chapter two explains the basic drilling and well construction, including drilling units, drilling operations, well control and well construction outline. In drilling operations, drilling, casing and cementing as main elements will be introduced. Losses and influx/kick will be explained in well control.

Chapter three introduces the background knowledge of a BOP system, including the BOP system structure, equipment and components, functions of the equipment and different requirements. This chapter also mentions some of the common system failure that might happen and the consequences of these. In the end of the chapter, a BOP reliability concept is proposed.

Chapter four implements a FMECA analysis on the BOP system, which contains an FME analysis and a CA analysis. It starts from the system definition, and proceeds to a failure mode analysis on different equipment and component. Finally, a CA analysis is implemented for different components.

Chapter five is the Bow-Tie analysis of BOP system, which is based on the results from the chapter four – the FMECA analysis. This model includes an FTA analysis and an ETA analysis and lead to a short conclusion in the end of the chapter.

Chapter six is reliability and prediction of a BOP system with an expected MTBF. This chapter introduces a reliability allocation and prediction, step by step. The results are meeting the expected MTBF.

Chapter seven discusses the general results of this thesis and proposes some future suggestion in this area of study.

1.5. Limitations

The reader is assumed to have basic knowledge of drilling operations in oil and gas industry, in addition, the reader is expected to be familiar with the terms used the courses in the University of Stavanger:

- RIS 500 Risk analysis and management
- RIS 510 Reliability Analysis
- RIS 520 Technical Safety

and/or the terms used in NORSOK standards.

The reader is also assumed to have knowledge of basic concepts related to subsea blowout preventer system.

2. Drilling and well construction basics

Drilling a well is a complex operation involving a series of highly specialized equipment and tools, as well as trained personnel located on-site, whether onshore or offshore, as well as an engineering and management team usually located at the office, off-site. Planning a well could years, while executing the well could take several months.
There are several aspects that go into planning a well and the actual drilling operation which will not be covered in this thesis. However, in this chapter some of the basic principles of drilling a well are described. [7]

2.1. Drilling Units

The well is drilled by a drilling unit. There are different types of drilling units depending on the location the well is being drilled.

Land rigs are used for drilling onshore wells and it is how the drilling industry started. There are a big variety of different types of land rigs today. They are often smaller and less expensive than their offshore counterparts.

Jack up rigs is offshore drilling units that float and can be towed by other ships to the planned well location. Once on location, it can lower three leg structures down onto the seabed to support the rig. Once the legs are lowered, the hull of the rig can be jacked up to a desirable height above the sea level. Due to limitations on the length of the leg structures, jack up rigs are limited to water depths up to ±400-500 ft.

Semi-submersible rigs will partially submerge themselves and remain floating on top of the sea during well operations. These rigs can keep their position by anchoring themselves to the seabed using anchors, or by using thrusters to keep the rig in place. Often combinations of these are used. Semi-submersible rigs can operate in water depths up to ±10000 ft.

For operation in the deepest waters, drill ships are used. Drill ships are like semi-subs but offer greater manoeuvrability and integrity in high seas due to the design of the ship. [8]

2.2. Drilling Operations

2.2.1. Drilling

Once a drilling unit is in place, the well can be drilled.
Drilling is done by lowering several joints of drill-pipe through the drilling tower (“derrick”) on the drilling unit. At the bottom of the drill pipe is a drill bit capable of breaking and drilling through the rock formation to reach the target, several thousand feet below the surface.

The entire drill pipe is then rotated. Rotation can be achieved in different ways, but in offshore drilling this is done by a motor connected to the top of the drill string. The motor is called a top-drive and can rotate the pipe, move the pipe up and down, and pump fluids down the drill pipe.

Drilling is done by connecting the bit at the bottom of the drill string with the formation, applying weight and rotation, while pumping fluids. A hole section is then drilled to its planned depth.

Drilling fluids is an important part of the drilling operation and has several functions. The fluid will cool down the bit and electronics in the drill string to prevent them for overheating. Fluids will also transport formation cuttings out of the hole as the well is being drilled. Drilling fluid also play a vital role in well control. As the well is drilled deeper, the formation pressure increases, causing formation fluid to enter the well or collapse the wellbore. To prevent this from happening, an equal or greater pressure must be applied to the formation. This is done by increasing the density of the drilling fluid as the well is drilled. However, increasing the mud density too high can cause weaker formations, shallower in the well to fracture, which will cause loss of drilling fluids. To get around this issue, steel pipes called casings, are installed in the well and cemented to the formation.

2.2.2. Casing

After a section has been drilled, several joints of casing are combined using dedicated casing handling equipment. The casing is lowered into the wellbore and installed at the bottom of the well. The top of the casing is often hung off in the wellhead.

For each section drilled, a slightly smaller diameter casing must be installed. The next bit would then need to pass through the inside of the last casing and must be slightly smaller again. Subsequently, the casing size and wellbore sections gets progressively smaller the deeper the well is.

2.2.3. Cementing

After a casing has been installed into the well, cement is pumped into the well. The cement travels inside the casing all the way to the bottom of the well. From here, the cement travel up again on the outside of the casing, between the casing wall and the formation. The cement is displaced to reach the correct position by using drilling fluids.

After the cement is set, the casing is fully supported, and drilling operations may continue. The cement is not only to support the casing, but also to isolate the annulus, the area between the casing and formation, ensuring no communication of pressure of fluids can travel up this way.

Once the cement is set, a new drilling assembly is lowered into the well and drilling of the next section can continue.

Chapter 2.2.1-2.2.3 written based on my own knowledge of drilling operation based on my 7 years work experience in oil and gas company in Stavanger, they refers at least how drilling, casing and cementing works in Norway oil and gas industry in the near 10 years.

2.3. Well Control

As the wells are drilled deeper, the formation pressure increases. It is therefore critical that well control is maintained all the time. Two main events indicate a well control incident.

2.3.1. Losses

Fluid loss indicates the drilling fluids are leaving the wellbore into the formation. This is a sign that the pressure in the well exceeds the formation strength, causing a fracture to occur. This can be caused by different events. Lowering the pipe into the well too fast could cause a piston effect to be transmitted to the formation that would exceed the formation strength. This is called a surge pressure. Simulations should be performed prior moving (tripping) pipe to avoid this to occur.

Another reason could be caused to the fluid density being too high compared to the formation strength. This could be caused by a weaker formation being exposed, or by choosing too high a fluid density for the section.

Loss of wellbore fluid will eventually cause the hydrostatic pressure of mud to decrease to balance the formation strength. If no action is taken, the hydrostatic pressure would reach a point where the formation pressure (deeper in the well), exceed the pressure exerted onto itself, causing a well kick or influx.

2.3.2. Influx / Kick

An influx means that more fluid enters the wellbore than is being supplied. This is caused by formation fluid that enters the wellbore. This occurs when the formation pressure exceeds the hydrostatic pressure exerted by the drilling fluid.

Just like the surge pressure, this could be caused by moving or tripping pipe too fast. Pulling pipe upwards too fast cause an under-pressure or vacuum to occur that allows fluid to enter the wellbore.

It can also be caused by having too low fluid density in the well. This could be the result of drilling into a high-pressure zone unaccounted for, or incorrect fluid density chosen due to incorrect pressure prognosis.

When drilling in hydrocarbon bearing reservoir zones, gas influx could become a serious event.
Due to the depth, the pressure and temperature are so high that the gas is compressed.
As the gas bubble is circulated to surface, the pressure is decreased causing expansion of the gas.

By using Boyles law, we know that if the gas can move freely up the well, the volume will be doubled when the pressure is halved. [9]

$P \times V = \text{constant} = P_1 \times V_1 = P_2 \times V_2$

Example of gas kick – Volume at TD vs Volume at surface:
P_1 = Surface Pressure: 1 bar
P_2 = Bottom hole well pressure: 800 bar
V_2 = Volume of gas kick taken: 4 m³
V_1 = Influx volume at surface

$P_1 \times V_1 = P_2 \times V_2$
$1 \text{ bar} \times V_1 = 800 \text{ bar} \times 4 \text{ m}^3$
$V_1 = (800 \times 4) / 1$
$V_1 = 3200 \text{ m}^3 = 3\,200\,000$ liter gas

2.4. Well Construction Outline

There are different types of wells that each includes certain types of operations. Exploration wells are aimed at drilling to a predetermined target to verify reservoir or hydrocarbon presence, performing well testing or logging and plugging back the well. A production well would instead of logging, install production tubing and production manifold (Xmas tree) to produce the reservoir fluids. [10]

In the example below, an exploration well is assumed:

- Drill 9-7/8" pilot hole
- Drill 36" hole section
- Run 30" Conductor
- Cement 30" Conductor
- Drill 26" section
- Run 20" casing & wellhead
- Cement 20" casing
- **Install riser and BOP**
- Drill 17-1/2" section
- Run 13-3/8" casing
- Cement 13-3/8" casing
- Drill 12-1/4" section
- Run 9-5/8" casing
- Cement 9-5/8" casing
- Drill 8-1/2" reservoir section
- Log reservoir
- Plug and abandon well
- **Retrieve riser and BOP**

The BOP is normally installed after the surface casing is installed, prior drilling into pressurized zones. It remains installed on the well throughout the well operations until the well is finally plugged back.

3. BOP System

3.1. Introduction to BOP system

A blowout preventer is critical well control equipment used in drilling operations. It is essentially a large valve that sits on top of the wellhead that can be closed in order to shut in the well in the event of unintentional flow from the well. It is the last line of defence against what could eventually lead to blowouts such as the recent Macondo well that changed the industry forever.

The BOP is typically installed on top of the wellhead after the shallow surface sections are drilled. The shallower sections do not normally have pressure above hydrostatic pressure and does therefore not require the BOP to be installed. After the surface casing is run and cemented, the BOP is landed on top, together with the drilling riser that connects the well to the rig. It will be installed here until the drilling scope is completed. The BOP will then be retrieved and used on the next well.

The BOP comes in different configurations and sizes. It can weigh as much as 400 metric tons for the subsea BOPs and can withstand pressures up to 15.000 psi (1034 bar), which is often required for the deeper wells with high formation pressure. The type of BOP used for a certain operation depends on the type of operation it is being used for, the characteristics of the well and whether the operation is conducted onshore or offshore, in shallow or in deep waters. [11]

3.2. BOP Stack components

The BOP stack consists of two main types of mechanisms to close in the well; Rams and Annular preventers. These are often combined in a drilling BOP stack.

3.2.1. Annular preventers

The annular preventer is an elastic doughnut shaped rubber element that can be closed around the pipe. Due to the elasticity of the rubber element, the annular preventer can seal around a variety of different shapes and sizes, even an empty wellbore. The benefit of using the annular preventer is that it maintains its sealing capabilities while moving the pipe. Giving the opportunity to trip (move drill pipe in or out of the well) while sealing the wellbore against a well control incident. [12]

3.2.2. Ram preventers

The ram preventers consist of pistons positioned opposite of each other that are pushed against the pipe in the wellbore.

Pipe rams form a seal around the drill pipe and seal the annulus. These can be used to shut in the well, while still maintaining the drill pipe intact. Pipe rams can be either fixed to a certain size of pipe, or variable to fit a range of pipe sizes.

Shear rams, or blind-shear rams, will seal the full wellbore area by shearing or cutting the drill pipe. This is often a last resort, and only used in extreme cases. [13]

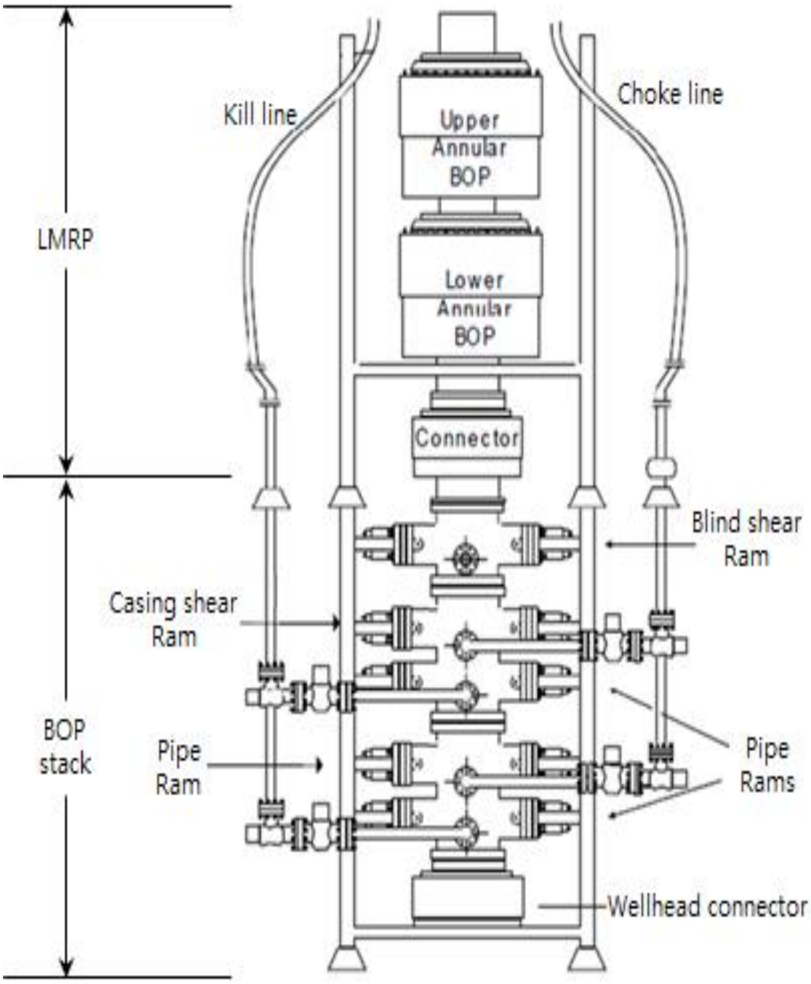

Figure 2: A BOP example.

3.2.3. Hydraulic connector

The hydraulic connector device is one of the important equipment in BOP system. It is mainly installed on the BOP or the lower part of the Christmas tree, it can also Installed on the lower marine riser package (LMRP). It is used connect the LMRP and the BOP but can quickly unlock or disconnect the LMRP and the ROP when emergency happens. [14]

3.3. BOP Activation

For onshore operations the BOP rams can be activated manually. This is also an option for offshore BOPs when drilling in shallow waters with jack-up rigs, where normally the BOP is situated on the rig. However, the BOP stack is most often operated by hydraulic pressure that is transferred from the control unit called accumulator, down to the BOPs rams and annular preventer.

The accumulator is located on the rig and consists of canisters filled with a hydraulic fluid and a gas cap. The gas cap will act as a piston towards the fluid. The gas is often an inert gas and is highly compressible, while the fluid is not compressible. This gives it the ability to instantly transmit power to the BOP when the accumulator is activated.

For deeper offshore wells there are other ways of activation due to the limitations that comes with operating in deep water with higher pressures:

1. Electrical signal through a cable
2. Acoustic signal
3. Mechanically with a remote operated vehicle (ROV)
4. Deadman switch (Automatic activation in event of lost power or hydraulic pressure) [15]

3.4. BOP requirements

Every country that is involved in active drilling operations, whether onshore or offshore needs to adhere to its own country's regulations for health, safety and environmental concerns and requirements.

For the Norwegian Continental Shelf (NCS), the Petroleum Safety Authority (PSA) has a list of regulations that all operators on the shelf must adhere to. Standards (NORSOK standards) are then used to guide operators into more specific actions and explanations.

The section specific to the blowout preventer can be found in the *Facilities regulation, section 49: Well Control Equipment*. [16]

The Well Control Equipment section is guided by the NORSOK D-001 and NORSOK D-010 standards.

3.4.1. BOP requirements found in NORSOK D-001

The NORSOK D-001 standard covers the requirements of design, installation, testing and functions of drilling facilities and their systems.

Well control systems are covered in chapter *6.35 Well Control System* and consist of a system or equipment that either monitor the well throughout different operations or provides a means of establishing a secondary barrier. The function of the secondary barrier is to take over in case the primary barrier envelope fails. In practical terms, this means if the drilling fluid is unable to hold back formation pressure, causing an influx or kick of formation fluid to enter the wellbore.

Furthermore, in Chapter 6.35.1, a list of rig equipment is given that makes up the well control system. The BOP, either a single or a dual BOP system, is a part of this list.

It is also specified that the BOP shall be connected to a choke manifold and a de-gasser system. These systems are used to control the flow of the kill and choke lines in a well control situation as well as removing gas from the drilling fluid.

Chapter 6.35.3 and 6.35.4 goes into detail regarding functional requirements for a surface blow out preventer and a subsea blowout out preventer respectively. The following topics are covered:

- Amount of different ram types and outlets required
- Dimensional requirements
- Metallurgy considerations (H_2S / CO_2 / Corrosion protection)
- Ram size consideration and hang off capacity
- Shearing and sealing capabilities
- Heat protection
- Testing requirements
- Bull-heading capabilities after activating shear ram
- Suspension of pipe
- Stripping pipe in and out safely
- LMRP disconnect capabilities (subsea only)

Chapter 6.42 BOP control system goes into detail about the activation of the BOP stack functions and monitoring of stack functions. It refers to OLF 070 recommendations:

- The BOP shall have the possibility to be activated from at least three locations on the rig or facility.
- The control panels shall clearly indicate the status of the functions (open/closed).
- All activation panels shall show pressure and volume readings
- Unintentional operation of functions shall be mitigated by having control panels secured within a cabinet or similar.
- All electrical equipment related to activation of BOP shall be explosion proof.
- A given set alarms shall be equipped on the panels
- Failure of a panel shall not affect other panels
- The accumulator unit shall be in a protected area
- Accumulator requirements as per API 16D

Chapter 6.42.2 Special requirements for MODU, describes specific control system requirements regarding subsea BOPs:

- Enough pressure shall remain after cutting pipe to disconnect the LMRP
- Corrections for sea water column (water depth) as well as temperature shall be made then considering accumulator capacity
- An independent acoustic or equivalent control system shall be available and have enough Pressure to operate two pipe rams, all shear rams, marine riser disconnect and mini choke and kill connectors
- The accumulators shall have enough pressure to close pipe rams, shear tubulars, seal wellbore, open LMRP connector and open mini choke and kill line connectors.
- A portable acoustic system control panel unit shall be available
- All seal areas for the control system exposed to seawater or well bore fluids shall be non-corrosive

Chapter 6.43 covers additional requirements for the blowout preventer in the event of drilling high-pressure, high-temperature (HPHT) wells. The definition of a HPHT well is a shut-in wellhead pressure of 690 bars or above and a static bottom hole temperature of 150C or above.

3.4.2. BOP requirements found in NORSOK D-010

The NORSOK D-010 covers the topic of well integrity in drilling operations and reference the BOP as a barrier element throughout the standard.

Chapter 15.4 – Drilling BOP (Table 4) covers the description, function, design, testing and verification and monitoring of the drilling BOP during drilling operations.

The description states that the “Drilling BOP” element consists of the wellhead connector and the drilling BOP with kill and choke lines.

The function of the BOP is to prevent flow from the wellbore to the environment and to provide a mechanical connection between the wellhead and BOP. The function of the BOP is to ensure the well can be sealed both with and without tools in the well.

The design part references the NORSOK D-001, API 53, API 16RCD and ISO 13533 regarding the construction and design of the BOP.

The BOP testing and monitoring requirements are listed in a separate table within the NORSOK D-010, the *Annex A – Test pressures and frequency for well control equipment.*
The table describes all the BOP elements, and goes into detail about what pressure they shall be tested to, when they should be tested, and how often they should be periodically tested.
Drilling operations must adhere to this testing regime, or apply for a deviation in the event a BOP test is deemed to lead to a less safe operation at the present time.

3.4.3. BOP requirements found in API RP 53

The API RP 53 standard serves the purpose to provide requirements of the installation and testing of blowout preventers of both onshore and offshore rigs.

The standard goes into function and design requirements of the blowout preventer’s pressure sealing components, as well as the required pressure testing regime for these.

The standard also covers the specific requirements linked to surface and subsea blow out preventers, as well as H2S service application.

More information about this can also be found in the NORSOK standards, presented below.

3.5. BOP failure

In order to improve the reliability and safety of deep-water blowout preventer systems, fault alarm and fault analysis equipment have also been developed. James McKay developed a set of deep-water blowout preventer health monitors [17], which combined the information of blowout preventer monitoring data, alarms and events. The health status of deep-water blowout preventers was displayed in real time based on the principle of traffic lights. When a serious fault occurs, it is displayed with a red light to inform the operator. Like a black box on an aircraft, a deep-water BOP data recorder Blackbox was developed by National Oilwell Varco (NOV). The black box stores the data on a server and can analyse the data after a serious incident occurs to find out the cause of the accident [18].

At present, there are still some deficiencies in the fault diagnosis research of deep-water BOP systems.

On the one hand, the deep-water BOP system has many components and complex structure. To construct a complete and accurate fault tree, the task is arduous and difficult, and the professional quality of the analyst is also high. However, the fault tree is complete and accurate. The degree directly affects the reliability and validity of the fault tree analysis results. The existing fault tree models need to be further improved.

Secondly, the fault tree model is not easy to expand, it is not easy to implement a quantitative analysis based on a fault tree model. On the other hand, the fault diagnosis technology of deep-water blowout preventer system should combine with the development of signal processing, computer technology, artificial intelligence, and pattern recognition technology to realize the diversification of fault diagnosis model and intelligent diagnosis technology. Therefore, it is necessary to carry out research on the fault diagnosis method of deep-water blowout preventer system in order to enrich the theory of deep-water blowout preventer failure diagnosis.

The existing fault diagnosis methods can be generally divided into three categories: fault diagnosis based on analytical models, fault diagnosis based on signal analysis, and fault diagnosis based on knowledge. Methods based on analytical models include parameter estimation, state estimation, and equivalent space methods. Methods based on signal analysis include wavelet transform and empirical mode decomposition method. Knowledge-based methods include expert systems, fuzzy set theory, artificial neural networks, Bayesian networks, decision trees, and so on.

Uncertainty is an important consideration when troubleshooting a deep-water blowout preventer system. First, due to the randomness, ambiguity and incompleteness of the data, there is a lot of uncertainty information in the fault reasoning process, which will greatly affect the accuracy of the fault diagnosis. Second, due to uncertainty, the same failure may show different symptoms of failure. Therefore, the results of fault diagnosis are more reasonable in terms of probability. [19]

3.6. BOP reliability

The reliability of deep-water blowout preventer system is extremely important to ensure the safety of deep-water drilling. At present, the research on the theory and technology of deep-water blowout preventer reliability has become an important hot topic. Flowler use Failure Mode and Impact Analysis (FMEA) and Fault Tree Analysis (FTA) techniques to analyse the reliability of the blowout preventer and hydraulic control system [20]. Holand collected data on the failure and failure of underwater blowout preventers and used fault tree analysis to evaluate the availability of the underwater blowout preventer system. [21-25]

The effects of common cause failure, incomplete repair, and incomplete coverage on the reliability of the electronic control system were studied. Although some progress has been made in the reliability research of deep-water blowout preventer systems, there are still some problems. The disadvantages of fault tree analysis and failure mode and impact analysis are that they are only suitable for reliability assessment of non-repairable systems, cannot consider the effects of time changes [26-27], and cannot distinguish common cause failures or severe fault conditions [28].

At present, the reliability models of important components of deep-water blowout preventers such as annular blowout preventers and wellhead connectors have not been established, and the factors affecting their reliability need to be further studied. In addition, the effect of the input voting scheme of the deep-water blowout preventer electronic control system on system reliability is not clear. The reliability model of the entire deep-water blowout preventer system, including the deep-water blowout preventer system and control system, has not yet been established.

Deep water blowout preventer system has a complex structure and many components, mainly including deep water blowout preventer systems and control systems. As shown in Figure 3: Deepwater BOP stack, the deep-water BOP system is generally equipped with annular preventers, rams, hydraulic connectors, and riser connectors. It can be regarded as a complex structure with both series and parallel connections. The electronic control system is a distributed control system developed by electronic modules such as input modules, output modules, and processor modules using redundant technologies. Therefore, for the reliability assessment of deep-water BOP systems, it is important to choose a suitable modelling method. At present, the commonly used system reliability evaluation methods mainly include Markov models, stochastic Petri nets, GO method / GO-FLOW method, Bayesian network, and so on. Various evaluation methods have their advantages and disadvantages. It is difficult to complete the reliability evaluation task of a deep-water blowout preventer system by using one method alone. Therefore, according to the structure and function characteristics of the deep-water blowout preventer system and the reliability issues to be studied, it is a reasonable solution to choose an appropriate modelling method.

In order to improve the reliability of the system, the configuration of the deep-water blowout preventer system uses redundant technology, and the Markov method is often used for reliability evaluation of redundant systems. The Markov method is capable of modelling and analysing repairable systems. It can describe systems with multiple states and can switch between multiple states. The Markov model is easy to solve, and multiple reliability indicators of the system can be obtained, such as reliability, availability, steady-state availability, and mean time between failures. However, Markov modelling methods face the problem of state explosion, that is, as the number of system components increases, the number of states of the system increases exponentially, so it is difficult to handle larger-scale systems.

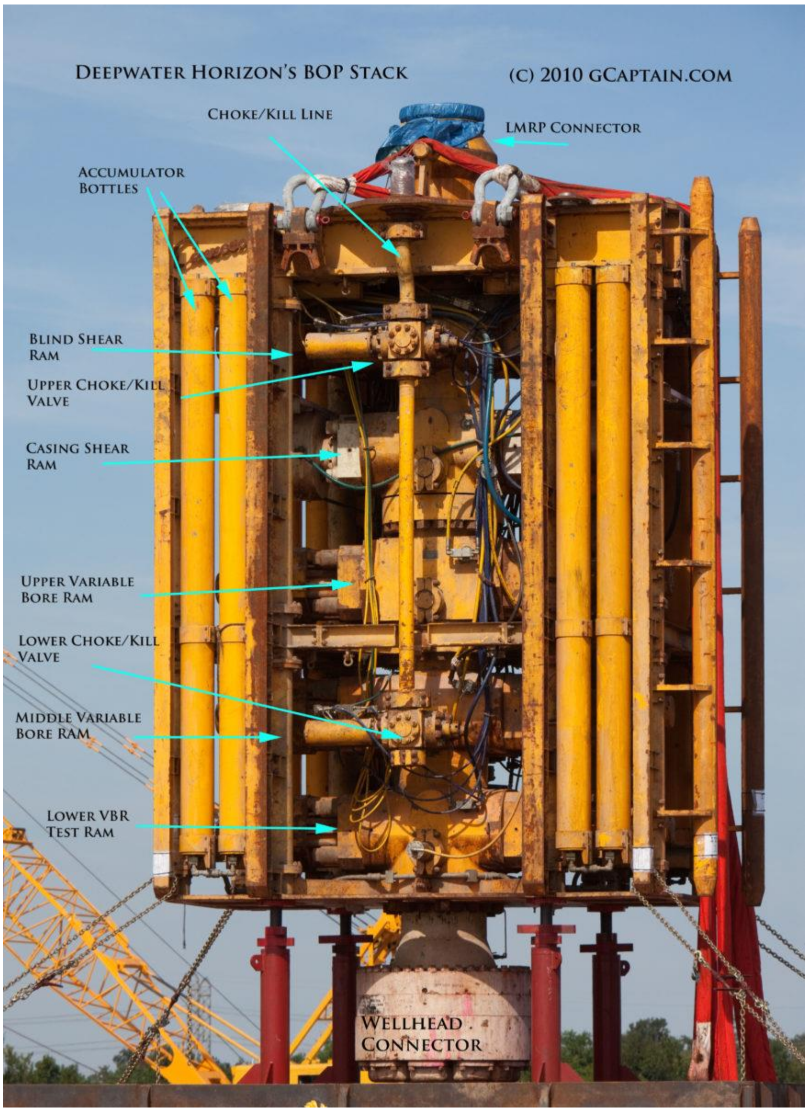

Figure 3: Deepwater BOP stack [42].

Due to the complex relationship between the components of the deep-water BOP system, the uncertainty is inevitable. Bayesian network is a powerful tool for expressing uncertainty knowledge and performing uncertainty reasoning and has been widely used in reliability and risk analysis in many fields.

Bayesian network is one of the most effective theoretical models in the field of uncertain knowledge and reasoning. The basic assumption of the Markov method is that the state of the system at the next moment is only related to the state of the current moment and has nothing to do with the state of the previous moment. Such assumptions limit the scope of the Markov method, because the state of many actual systems is not only affected by the state of the previous moment, but also by other factors that have dependencies on each other. Bayesian network modelling methods can overcome these shortcomings.

In addition, Bayesian networks have good scalability, model parameters can be updated in real time, and models of complex systems can be established. Therefore, a dynamic Bayesian network can be used to establish a reliability assessment model for a deep-water blowout preventer system.

One disadvantage of Bayesian networks is that there are no specific semantic rules to guide the establishment of models [29]. To solve this problem, a research idea is to transform the traditional reliability model into a Bayesian network model. The fault tree model has been successfully mapped to a Bayesian network [30]. Boudali and Dugan proposed a method to transform a dynamic fault tree into a Bayesian network [31]. Montani developed a set of software that can automatically transform dynamic fault trees into corresponding dynamic Bayesian networks [32].

4. FMECA Analysis of BOP

4.1. FMECA analysis method

Failure Mode and Effect Criticality Analysis (FMECA) is developed by reliability engineering, which mainly analyses the reliability and safety of the system. Through the recognition and evaluation of potential failures and the consequences of such failures, measures to eliminate or reduce the chance of potential failures are identified [21]. The purpose of the FMEA analysis of the Deep-water BOP control system is to illustrate the different failure modes of the equipment related to the control system function. There may be multiple failure modes for a certain device in the system, which may have many different effects on the control system. Special attention should be paid to the analysis. The entire control system should be analysed by FMECA method.

The analysis process in this thesis is set up as following:

1. Set up a description of the main components of the system. (See chapter 2.)
2. Complete basic definitions of the system before the analysis, which mainly include:
    a. System configuration parameters and working environment
    b. Find out maintenance content and frequency
    c. System level analysis
    d. Severity category
    e. Critical ranking
    f. Collect historical failure data
3. FMECA of the system failure mode: list all possible failure modes of the system, analyse the causes and perform a quantitative analysis of the degree of hazard.
4. FMECA of the equipment failure mode: find all possible failure modes of each device, analyse the causes of the failure, evaluate its severity and probability level, and use the matrix diagram to analyse the degree of hazard.
5. Apply a Bow-Tie analysis based on results from FMEC analysis; select the failure mode with high risk as the top event to build the tree analysis.
6. Combine the results from FMECA and Bow-Tie analysis and give analysis conclusions.

4.2. Basic system definition

4.2.1. System configuration parameter

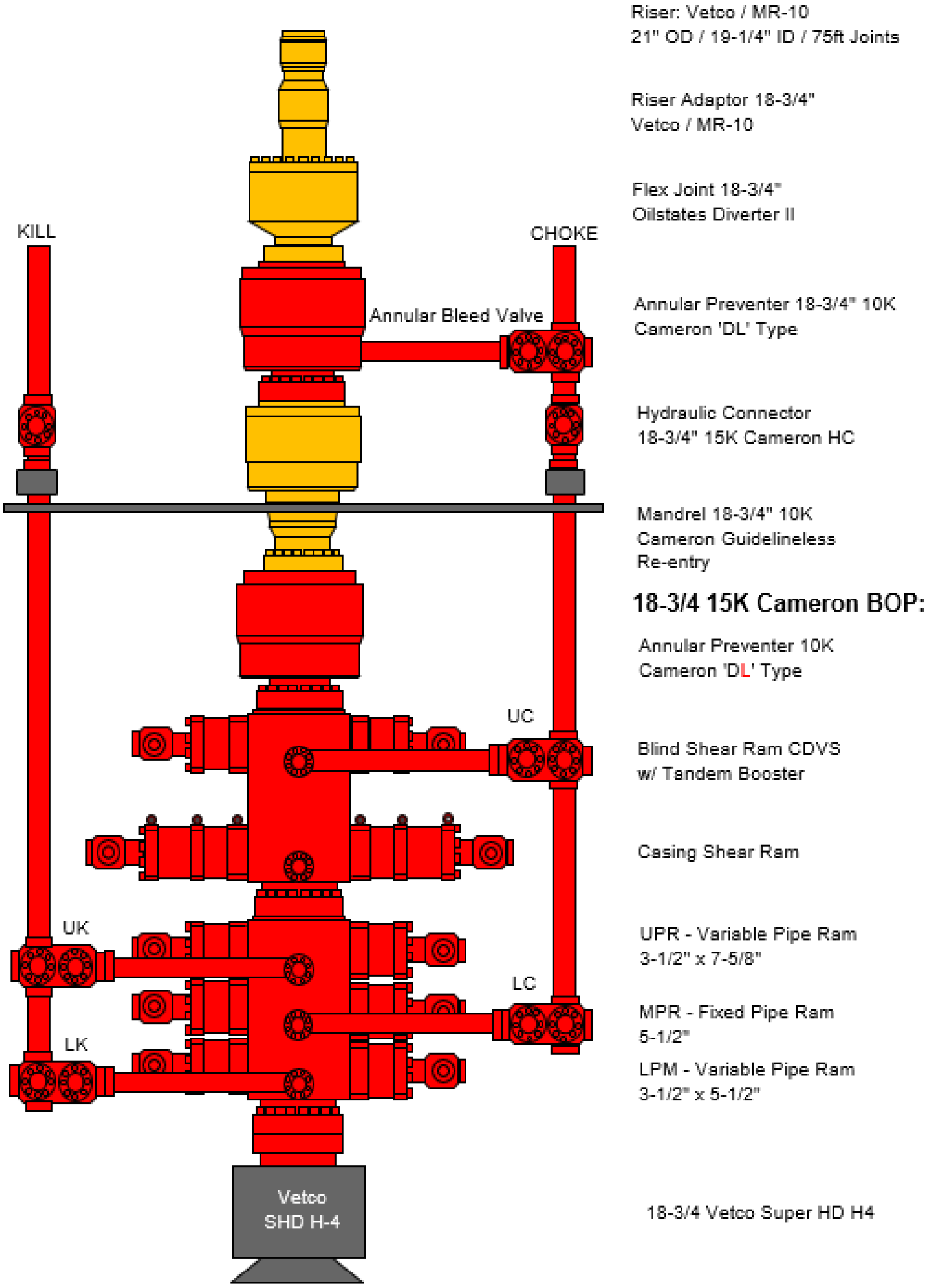

Figure 4: Cameron BOP - 18-3/4" 15K [43].

As shown in Figure 4: Cameron BOP - 18-3/4" 15K, there are two annular preventers, one in the LMRP, one in the subsea BOP stack. There is also blind shear ram, Casing shear ram and pipe rams. Example of typical and the specifications are listed in the following table: [33]

Equipment	Manufacturer	Type	Specifications/Comments
LMRP	Cameron	18-3/4” - 15K	**Annular Preventer**: Cameron DL (high temp). 690 bars. Temp rating 7.2°C to 82.2°C for continuous operation. Temp rating 126.7°C for extreme one-hour operation. Material: Nitrile, suited for OBM. Double bleed valve below annular
BOP stack	Cameron	18-3/4” - 15K	**Annular Preventer:** Cameron DL (high temp). 690 bars. Temp rating 7.2°C to 82.2°C for continuous operation. Temp rating 126.7°C for extreme one-hour operation. Material: Nitrile, suited for OBM
	Cameron	18-3/4” - 15K	Double cavity. Studded top and flanged bottom connections. 1034 bar. **CDVS Blind Shear Rams:** 1034 bar. Temp rating: -1°C to 177°C. Operating pressure 3000 psi. Material: Nitrile, suited for OBM. **Super Shear**: Temp rating: -1°C to 177°C. Operating pressure 5000 psi. **UPR: Fixed 5” HT Rams**: 1034 bar. Temp rating: -1°C to 177°C. Material: Nitrile, suited for OBM
			Triple cavity. Clamped top and bottom connections. 1034 bar. **MPR**: Variable Bore Rams 3.5” – 7.625”, 1034 bar. Temp rating 4°C to 82°C. Material: Nitrile, suited for OBM **LPR**: Fixed 5” HT Rams, 1034 bar. Temp rating: -1°C to 177°C. Material: Nitrile, suited for OBM

Table 1: Example of BOP ram specifications.

4.2.2. Operation environment

Here is a general operation environment of most of the deep-water subsea BOP:

Environment conditions	Parameter
Depth	Maximal operation depth depends on the pressure.
Seawater density	Average: 1024.8kg/m^3
Temperature	Depends on the depth
Seawater oxygen content	Average: 3.2mg/L

Table 2: BOP operational environment.

4.2.3. Maintenance during operation and lifetime

According to the definition of reliability, reliability depends on the tasks of the product and is related to the expected environmental and time factors. Therefore, before determining the reliability requirements, we must first accurately define the tasks of the system and divide the processes according to the different operating state.

After the BOP is installed on the wellhead, it enters the stage of operation. Any failure of the system during the operation phase may lead to downtime, resulting economic losses and even potential casualties. According to regulations, the entire blowout control system must be regularly tested for function and pressure as specified. The test contents are shown in Table 3: BOP testing. [4]

Test component	Test content
Annular Preventer	Full load pressure test before casing
	70% full load pressure test after casing, before cement
	Seal the drill pipe regularly
Shear Ram	Full load pressure test before casing
	Full load pressure test after casing, before cement
	Regularly pressure test to rated pressure
	Daily open and shut function test
Kill Valve	Full load pressure test before casing
	Check under all BOP test

Table 3: BOP testing.

The entire BOP system needs to be fully maintained and tested both before the underwater installation and after the drilling is completed. The major components should also be maintained every 3 to 5 years [4]. According to the operation records of drilling companies, the main maintenance contents are shown in Table 4: BOP maintenance content:

Component	**Maintenance content**
Flex Joint	Cleaning and check whether there is abnormal abrasion, and check whether the bolts are installed correctly.
Annular Preventer	Cleaning, check whether there is damage or abrasion both inside and outside, check whether the rubber core needs to be replaced, and test pressure to 70% of the rated operation pressure.
Hydraulic Connector	Cleaning, check internal and external damage, check sealing surface, test locking mechanism
Shear Ram	Cleaning, check the sealing, check whether there is any damage on the gate and the gate chamber, test the pressure to 75% of the rated operation pressure, test the locking mechanism.
Kill Valve	Cleaning, lubricate, test the pressure to operation pressure.
Control System	Check whether any leaks on the power fluid transmission line, check the control box base and the plug, test the pressure vessel, replace the filter device, and check the control cable. Perform functional tests on the blowout preventer system.

Table 4: BOP maintenance content.

The basic task of the well control system in the use phase is to shut the well quickly. There are two methods to shut the wells: The hard method and the soft method. The so-called hard shut is to immediately shut down the blowout preventer when overflow is found, while the choke valves are closed. The soft shut is to shut the blowout preventer after choke valves are opened. The hard shut is easier and faster. However, the hard shut will cause a “liquid strike” effect on the formation due to the sudden ejection of fluid in the well and the circulation speed of drilling fluid suddenly reduced to zero, which may have undesirable consequences to the wellhead device and the formation. The soft shut of the well can gradually stop the ejected fluid without violent “liquid strike” on the formation [34].

4.2.4. BOP system levels

When implementing the FMECA on the BOP system, the analysis object should be clearly defined. The system levels can be defined according to the functional level relationship and the hardware structure level relationship.

The analysis level of the BOP well control system is determined as shown in Figure 5: BOP system level analysis:

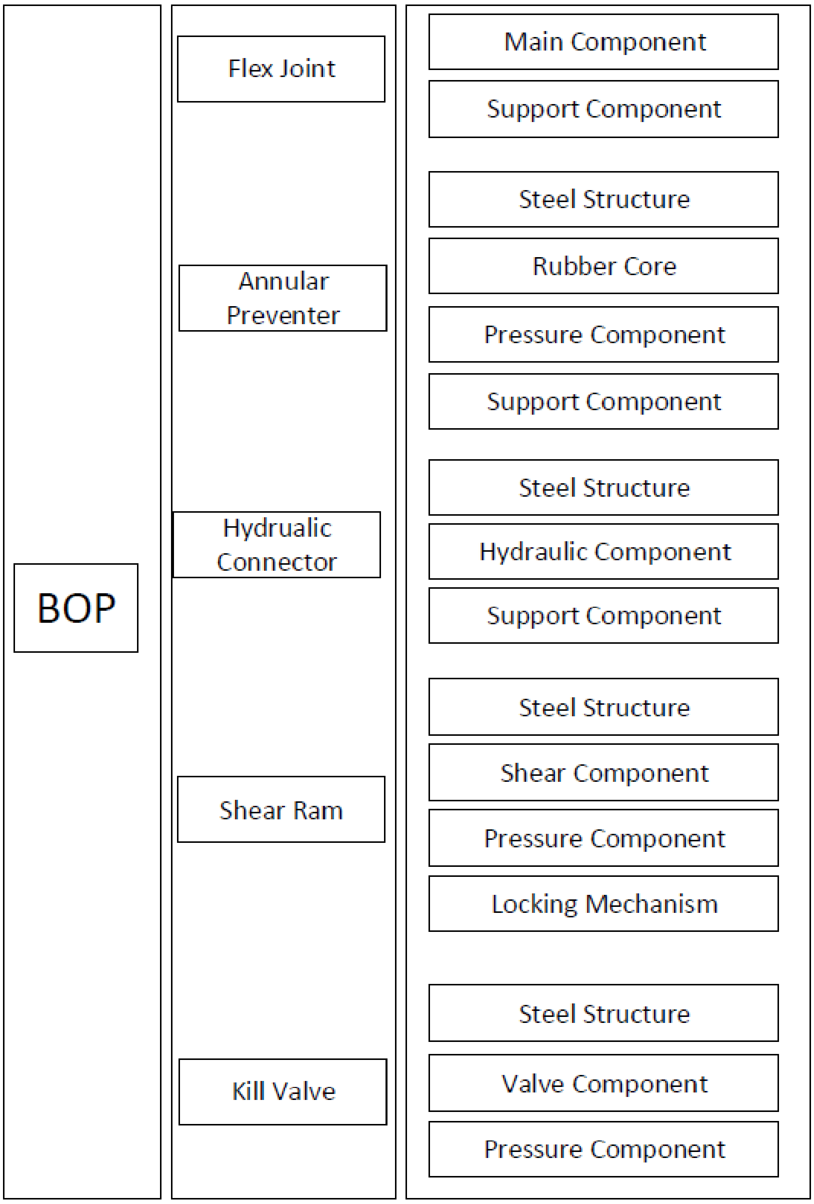

Figure 5: BOP system level analysis.

4.2.5. Severity classification of the components

Severity refers to the severity of the final impact of the failure mode, and the severity level is a measure of the worst potential consequences of system failure. According to MIL-STD-882 [35], there are mainly four categories of severity:

Category	Description	Criteria
I	Catastrophic	Could result in death, permanent total disability, or irreversible severe environmental damage that violates law or regulation.
II	Critical	Could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, or reversible environmental damage causing a violation of law or regulation.
III	Marginal	Could result in injury or occupational illness resulting in one or more lost workday(s), or mitigatable environmental damage without violation of law or regulation where restoration activities can be accomplished.
IV	Negligible	Could result in injury or illness not resulting in a lost workday, or minimal environmental damage not violating law or regulation.

Table 5: Severity category.

4.2.6. Critical ranking

FMCA (Failure mode criticality assessment) can be qualitative or quantitative. For qualitative assessment, according to the same standard MIL-STD-882 [35] as in 4.2.5, the failure probability could be defined in five levels.

Description	Level	Individual Item	Fleet
Frequent	A	Likely to occur often	Continuously experience
Probable	B	Will occur several times	Will occur frequently
Occasional	C	Likely to occur some time	Will occur several times
Remote	D	Unlikely but possible to occur	Unlikely, but can reasonably be expected to occur
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced	Unlikely to occur, but possible

Table 6: Qualitative critical ranking.

The failure mode may then be charted on a criticality matrix using severity code as one axis and probability level code as the other.

4.3. Failure mode analysis of BOP

4.3.1. Data Sources

Although there is a certain amount of research on BOP reliability, most of it is not for public use. The data used in chapter 4.3 mainly come from the SINTEF Report [36]. Data in this report comes from the drilling reports of nearly 100 deep-water wells in the U.S. continental shelf and the Gulf of Mexico. The drilling depth is between 400m and 2100m. The system configuration and structural of the BOP system is matching the BOP system object in this thesis.

4.3.2. Preliminary analysis of failure data

4.3.2.1. Drilling depth distribution

The failure data of BOP system in the SINTEF report comes from 83 well reports. The drilling water depth distribution of wells is shown in Table 7: Drilling depth distribution. The total operational time in the table refers to the total time of the BOP system under operation. If the BOP system is removed during the operation due to a failure, the waiting time is still included in the working time. If the well is temporarily abandoned due to other special reasons, and the BOP system is removed from the wellhead, this type of time would not be calculated as operation time.

Water Depth (meter)	Number of wells	Total operation time (day)
400-600	30	1350
600-800	10	573
800-1000	10	521
1000-1200	18	644
1200-1400	6	475
1400-1600	2	140
1600-1800	4	169
1800-2000	3	137
Sum	83	4009

Table 7: Drilling depth distribution.

4.3.2.2. BOP equipment failure distribution

The equipment failure distribution based on table 7 from chapter 4.3.2.1 is shown on following figure:

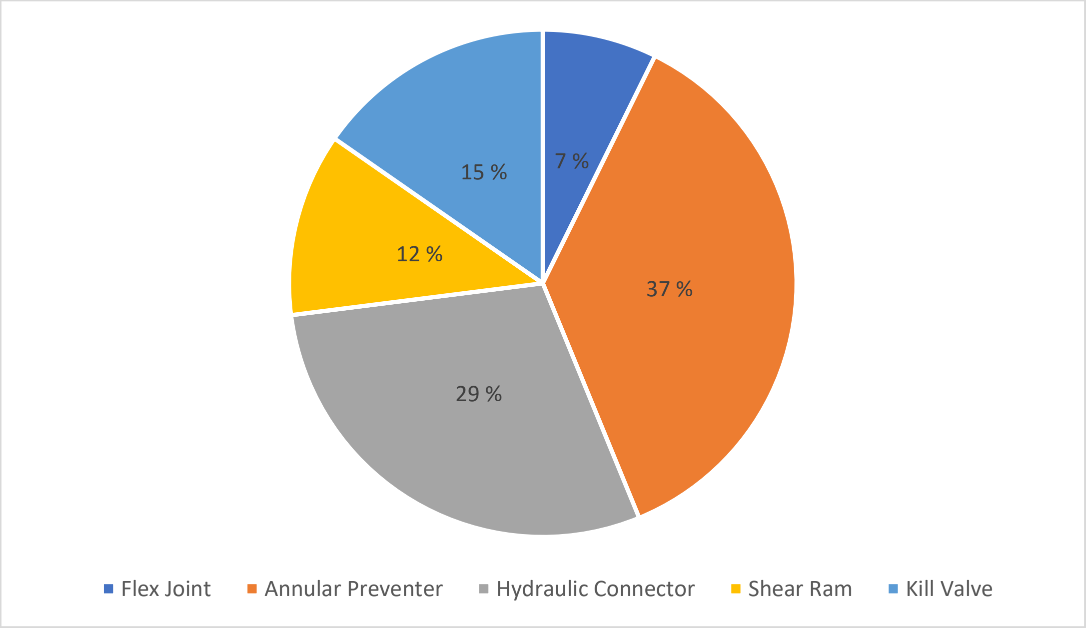

Figure 6: BOP equipment failure distribution.

It is seen from the figure that the annular preventer and hydraulic connector are the two parts with most failures, flex joint, kill valve and shear ram have relatively fewer failures.

4.3.2.3. BOP equipment downtime

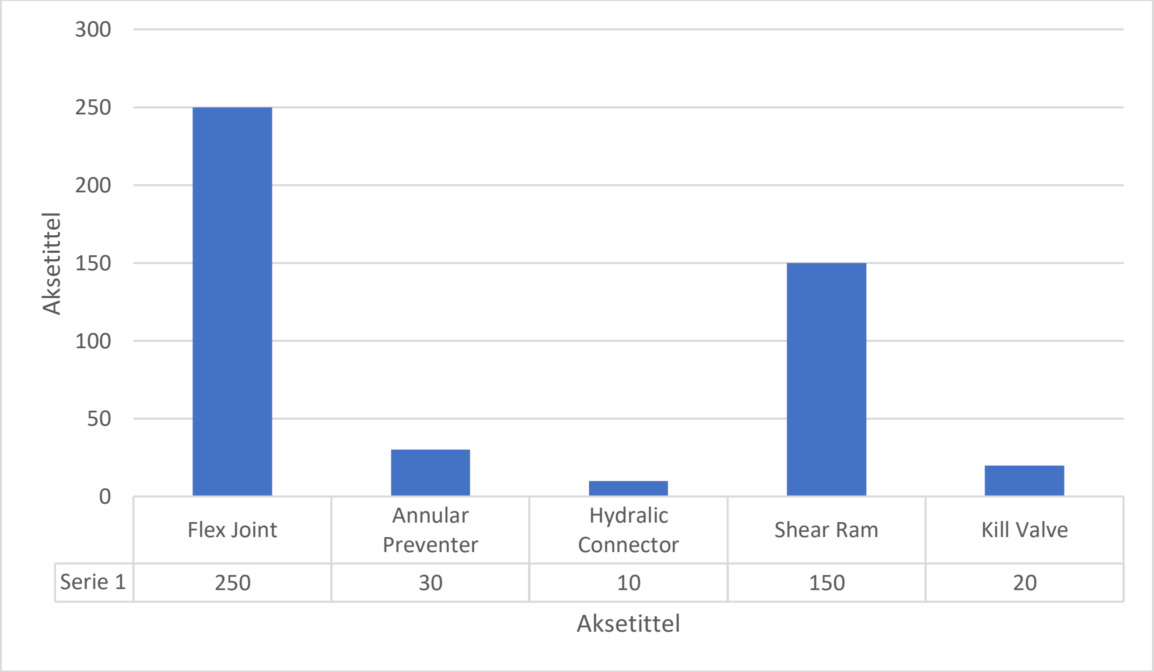

Figure 7: BOP equipment downtime.

As shown from the above figure, the downtime caused by flex joint and shear ram are much more than other equipment. However, it must be noted that the number of failures of the flex joint is actually very small (Figure 6 from chapter 4.3.2.2). But the failure of flex joint would cause extra-long time to get the whole BOP system back to normal operation. [37]

4.4. FEMCA analysis of equipment

Based on the existing historical data from the SINTEF report, take the entire blowout preventer system as the analysis object, the failure modes of each device will be listed in detail, and the damage degree of each failure mode will be calculated.

There are two purpose of FMECA analysis of the entire system: First, find out the common failure modes of each device, which will help the later FMECA analysis of the equipment and avoid ignoring any important failure modes. Second, calculate the failure modes for each device and the damage degree, which will help to determine the top event for later Bow-Tie analysis in Chapter 5, and provide a basis foundation for the reliability allocation in Chapter 6.

List up failure mode for each equipment, find out the severity of each failure mode.
Calculate the criticality numbers for each failure mode.
Discuss the results from calculation.

Input data for calculation are collected from the SINTEF report [36]:

Basic failure rate: λ

Failure mode ratio: α

Conditional probability: β

Mission phase duration: t

Criticality numbers: $Cm = \lambda\alpha\beta t$

Item criticality number: $$Cr = \sum_{n=1}^{N}(Cm)n$$

Equipment	Failure mode	Failure reason	Impact for system	Severity	Failure mode criticality					Item criticality number
					α	β	λ	t	Cm	Cr
Flex Joint	Leakage outside	Body rupture, Rubber failure, Seal failure	Blowout and a lot downtime	II	1	0.2	0.2494	45	2.24	Category II: 2.24
Annular Preventer	Well is not sealed good enough	Rubber core is damaged and failed	Less affected. Short downtime	II	0.492	1	1.6372	45	36.25	Category I: 18.12 Category II: 36.37 Category IV: 0.12
	Leakage outside	Body rupture, top seal failed	Blowout and a lot downtime	II	0.008	0.2	1.6372	45	0.12	
	Failed to open	Rubber core aging and deformation	Less harmful and short downtime	I	0.492	0.5	1.6372	45	18.12	
	Switch failure	Hydraulic components failure leads to oil leakage	Affect the response time and may cause accident	IV	0.008	0.2	1.6372	45	0.12	
Hydraulic Connector	Well is not sealed good enough	Seal failure	May cause some downtime	II	0.4	1	0.6177	45	11.12	Category II: 12.51 Category III: 9.46 Category IV: 1.11
	Leakage outside	Body rupture, top seal failed or side seal failure	Leakage and Blowout in worst case	II	0.1	0.5	0.6177	45	1.39	
	Failed to shut	Hydraulic components failure leads to oil leakage, piston deformation	Cause a certain downtime and may cause an accident	IV	0.1	0.4	0.6177	45	1.11	
	Failed to start	Hydraulic components failure, Locking mechanism failure	Cause longer downtime	III	0.3	0.9	0.6177	45	7.51	

	Cannot lock	Locking mechanism failure	Cause longer downtime, may cause an accident	III	0.1	0.7	0.6177	45	1.95	
Shear Ram	Leakage outside	Metal seal ring failure, hook failure	Less affected. Short downtime	II	0.369	0.4	1.2598	45	8.98	Category II: 1.86 Category IV: 1.59
	Unlock failure	Hydraulic components failure leads to oil leakage	May cause significant accident	IV	0.594	0.1	1.2598	45	3.37	
	Cannot lock	Hydraulic components failure leads to oil leakage	Cause a certain downtime	II	0.01	0.5	1.2598	45	0.28	
Safety Valve	Leakage inside	Sealing failure in valve	Less harmful and short downtime	I	0.5	0.1	0.3820	45	0.86	Category I: 1.59 Category II: 1.86
	Leakage outside	Sealing failure at flange	Leakage and Blowout in worst case	II	0.33	0.2	0.3820	45	1.13	
	Fail to start	Hydraulic components failure	Affect the system shutdown, may cause a certain downtime	II	0.085	0.5	0.3820	45	0.73	
	Fail to shut down	Hydraulic components failure, spring failure	Cause some short downtime	I	0.085	0.5	0.3820	45	0.73	

Table 8: FME analysis of main equipment in BOP system.

From the analysis results of Table 8: , among all 17 failure modes, there are 3 failures have severity IV. Combining the severity and probability of occurrence of each failure mode, the most harmful failure modes in category IV is the ‘hydraulic connector is unlocked’ failure. Due to the complex and changing climate at sea, when the weather is terrible such as typhoons, it is often necessary to start the emergency well abandonment procedure. It means to cut the drill pipe and unlock the hydraulic connector, disconnect the platform from the wellhead to avoid major safety accidents and ensure the platform and the safety of people and property.

In emergency abandonment process, if the hydraulic connector cannot be quickly unlocked, it may cause extremely serious consequences. Although the failure of unlocked hydraulic connector is mostly found during abandonment process, there is almost no record of major accidents due to this failure mode, but due to the high incidence of this failure, it still ranks as the most harmful one in all failure modes.

The failure mode ‘shut-off failure of the shear ram’ ranks as the second most harmful. This is also a serious failure mode could happen for the system. The shear ram blowout preventer is the core equipment of the entire well control system and is responsible for closure of the well for long term. This failure often brings hundreds of hours of downtime, and the shear ram blowout preventer cannot respond in time during a blowout, it may cause an uncontrollable blowout.

The failure mode ‘shut-off failure of annular preventer’ is also something that triggers a severity IV failure. However, the probability of occurrence of this failure mode is relevant low. The possibility of causing an accident by this failure mode is not high and therefore the ranking is third place.

Among the failure modes in severity category II and III, there are some failure modes with high harmful degree, such as ‘opening failure of shear ram’ and ‘the blowout preventer is not well sealed’. These failure modes might not cause a major accident, but because of to the high economic loss based on high probability of occurrence and longer downtime. They were ranked as severity category II and III. In deep sea drilling operations, every minute of downtime will bring huge economic losses. Therefore, from this perspective, the damage of this type of failure is not lower than that of type IV failure, and it should also be given enough attention.

4.5. FME Analysis for components

Based on the FMECA analysis of equipment in the previous section, this section conducts a further analysis of the impact of failure modes and the degree of damage on important components in the system. The analysis work includes: listing up all the failure modes of important components in the equipment, finding possible causes of each failure mode, evaluating the severity level of each failure mode according to the final impact, proposing some corresponding measures, and output the FMECA analysis table for components.

4.5.1. FME analysis for components

Component	Failure mode	Failure mode code	Failure reason	Impact for system	Severity	Qualitative critical ranking	Corresponding measures
Flexible component	Rubber failure	F1	Steel plate fracture, rubber aging, degumming	Can cause leakage	II	B	Replace the rubber
	Excessive wear on inner wear	F2	Using time is too long	Can cause leakage	II	A	Regular check and replacement
	Positioning pin broke	F3	Poor quality, corrosion damage	Can cause leakage	II	E	Replace the positioning pin
	Sealing failure between spherical pressure ring and outer body	F4	Seal aging and damage	Can cause leakage	II	B	Replace the seal
	Anti-rotation pin broke	F5	Corrosion damage	Can cause leakage	I	E	Replace the anti-rotation pin
Equipment body and other support component	Internal body crack	F6	Material or processing defects	Can cause leakage, may trigger blowout in worst case	II	E	Repair the crack

	Seal ring failure	F7	Seal corrosion, seal ring failure	Can cause leakage, may trigger blowout in worst case	I	D	Repair or replace the seal
	Anti-loosening flange failure	F8	Thread failure	Can cause leakage	II	E	Repair or replace the thread
	Excessive wear	F9	Using time is too long	May lead some downtime	I	D	Regular check and replacement

Table 9: FME analysis of components in flex joint

Component	Failure mode	Failure mode code	Failure reason	Impact for system	Severity	Qualitative critical ranking	Corresponding measures
The Annular preventer body	Body/shell crack	A1	Material or processing defects	Can cause leakage, may trigger blowout in worst case	II	E	Repair the crack
	Top thread failure	A2	Corrosion, damage due to uneven pressure	Can cause leakage, may trigger blowout in worst case	II	D	Repair the thread
	Seal failure between top cover and seal	A3	Seal ring aging and damage	Can cause leakage, may trigger blowout in worst case	II	D	Replace the seal ring and the groove
	The claw block can't move	A4	Corrasion at claw block	Almost no effect	I	E	Clean and lubrication
The rubber core	Rubber core degumming and tearing	A5	Bad rubber core material and processing quality, fatigue damage	Well is not sealed good enough	II	A	Replace the rubber core
	Poor rubber elasticity	A6	Rubber aging and deformation	May lead some downtime	I	A	Clean and replace the rubber core
	Bracing break	A7	Fatigue damage and bad quality	Well is not sealed good enough	II	D	Replace the rubber core

The hydraulic component	Piston sealing surface damage	A8	Excessive wear and scratches	Affect the response time and may cause accident	III	D	Repair the piston
	Piston sealing surface failure	A9	Corrosion, aging and damage of the seal	Affect the response time and may cause accident	III	B	Replace the sear ring
	Piston sealing surface corrosion	A10	Well fluid corrosion	Affect the response time but will not lead too long downtime	II	C	Repair the surface
	Damage inner cylinder	A11	Excessive wear and scratches	Affect the response time and may cause accident	III	C	Repair the cylinder
	Cylinder crack	A12	Material or processing defects	Affect the response time and may cause accident	IV	E	Repair the cylinder
Other support component	Dust seal ring failure	A13	Aging of the seal	May lead some downtime	II	C	Replace the sear ring
	Dust seal ring groove failure	A14	Corrosion of the groove	May lead some downtime	II	D	Replace the sear ring groove
	Damaged in wear plate	A15	Excessive wear	Almost no downtime	I	C	Regular check and replacement
	Screw failure	A16	Screw crack or corrosion	May affect the open and shut of the well	III	E	Repair or replacement
	Support tube deformation and crack	A17	Material or processing defects, corrosion damage	May affect the open and shut of the well	III	E	Repair the crack

Table 10: FME analysis of components in annular preventer.

Component	Failure mode	Failure mode code	Failure reason	Impact for system	Severity	Qualitative critical ranking	Corresponding measures
The ram preventer body/shell	Crack on the body/shell	R1	Material or processing defects	Can cause leakage, may trigger blowout in worst case	II	E	Repair the crack
	Upper seal surface damage	R2	Corrosion and scratches	Well is not sealed good enough, may lead some downtime	II	B	Repair the seal
	Upper seal surface failure	R3	Seal ring corrosion, deformation, seal groove corrosion	Can cause leakage, may trigger blowout in worst case	II	B	Replace the seal
	Thread failure at side hole	R4	Corrosion, uneven pressure, processing error	Can cause leakage, may trigger blowout in worst case	II	D	Repair the screw
The ram	Shaft hook broke	R5	Fatigue fracture, corrosion damage	May lead long downtime	III	E	Replace the damaged parts
	Front ram seal failure	R6	Rubber core fatigue damage, aging, corrosion, improper operation damage	May lead a certain downtime	II	B	Replace the seal
	Upper ram seal failure	R7	Seal aging, well pressure damage, top seal pin broke	May lead a certain downtime	II	B	Replacement
	T shape slot failure	R8	Fatigue fracture, corrosion damage	May lead long downtime	III	D	Repair or replacement

	The shear blade is damaged	R9	Insufficient blade strength, improper operation	May cause big accident	IV	D	Replace the blade
	Blade seal failure	R10	Scratched by cuttings, aging seal, well pressure broken	May lead a certain downtime	I	D	Replace the seal
	Screw failure at shear blade	R11	Corrosion damage	Well is not sealed good enough, may lead some downtime	I	E	Replace the screw
	Positioning pin failure	R12	Unknow object stuck, deformation	May lead a certain downtime	II	E	Clean and repair
	Robber core failure	R13	Robber core broken or disconnection	Well is not sealed good enough, may lead some downtime	II	E	Replace the component
	Adjustable ram deformation	R14	Too high pressure	Well is not sealed good enough, may lead some downtime	II	E	Replace the component
The hydraulic component	Main piston seal failure	R15	Sealing ring aging and broken	Causes a certain downtime, and may cause accidents when closing the well	IV	D	Replace the seal
	Excessive wear in main piston	R16	Long-term use, excessive use and loose	Causes a certain downtime, and may cause accidents when closing the	IV	E	Regular check and replacement

				well			
	Damage inner cylinder	R17	Excessive wear, scratches, cracks	Causes a certain downtime, and may cause accidents when closing the well	IV	D	Repair seal surface
	Main piston rod failure	R18	Mechanical impact, improper operation leads to deformation, body scratches	Causes a certain downtime, and may cause accidents when closing the well	IV	D	Repair piston rod, proper operation
	Failure between cylinder cover and piston rod seal	R19	Sealing ring aging, damage, corrosion	Causes a certain downtime, and may cause accidents when closing the well	IV	D	Replace the piston rod seal
The side door	Side door seal failure	R20	Sealing ring aging, sealing support frame deformation, corrosion, damage	Causes a certain downtime, and may cause accidents when closing the well	III	C	Replace the seal
	Sealing failure of side door and piston rod	R21	Sealing ring aging, damage, corrosion	Causes a certain downtime, and may cause accidents when closing the well	IV	D	Replace the seal and piston

	Broken side door bolt	R22	Corrosion cracking	Causes a certain downtime, and may cause failure when closing the well	IV	C	Replace the bolt
The locking mechanism	Wedge block at locking mechanism stuck	R23	Deformed wedge block, stuck due to excessive friction	Causes longer downtime, may lead to accidents	III	B	Repair damaged part
	Unlocking piston seal failure	R24	Sealing ring is aging or damaged. Excessive wear of piston	Causes longer downtime, may lead to accidents	III	E	Replace the seal
	Sealing failure of cylinder cover of locking mechanism	R25	Sealing ring failure, screw breakage, thread failure	Causes longer downtime, may lead to accidents	III	E	Replace or repair damaged parts

Table 11: FME analysis of components in ram preventer.

Component	Failure mode	Failure mode code	Failure reason	Impact for system	Severity	Qualitative critical ranking	Corresponding measures
The body/shell	Body/shell crack	H1	Material or processing defects	Failure of the switch may cause a major accident	IV	E	Repair the crack
	The bolt connecting the shell and the flange is broken	H2	Corrosion damage	Failure of the switch may cause a major accident	IV	C	Replace the bolt
	Corrosion and damage of thread	H3	Corrosion, uneven pressure	Failure of the switch may cause a major accident	IV	D	Replace the thread
	Seal at the connection between the shell and the flange fails	H4	Seal deformation and damage	Failure of the switch may cause a major accident	IV	C	Replace the seal
Hydraulic components	The main piston is stuck	H5	Piston deformation	Failure of the switch may cause a major accident	III	E	Replace the piston
	The seal between the main piston and the casing fails	H6	Sealing ring aging, pressure damage	Causes a certain downtime, and may cause accidents	III	C	Replace the seal
	Sealing failure between	H7	Sealing ring aging, pressure	Causes a certain downtim	III	C	Replace the seal

	locking piston and casing		damage	e			
	Failure to unlock the piston seal	H8	Sealing ring aging, pressure damage	May cause downtime, multiple failures may cause accidents	II	C	Replace the seal
	Damage inner the cylinder	H9	Excessive wear and scratches	Failure of the switch may cause a major accident	III	B	Repair the cylinder
	Piston damage	H10	Excessive wear	Failure of the switch may cause a major accident	III	C	Replace the piston
Other support components	Metal seal failure	H11	Deformation failure, installation error	Lead to leakage and blowout in the worst case	II	A	Replace the metal seal
	Hook failure	H12	Corrosion damage, fracture, deformation, excessive wear	Failure of the switch may cause a major accident	II	C	Clean and replace the component

Table 12: FME analysis of components in hydraulic connector.

Component	Failure mode	Failure mode code	Failure reason	Impact for system	Severity	Qualitative critical ranking	Corresponding measures
The body/shell	The body/shell crack	S1	Material or processing defects	Leakage inside	II	E	Repair the crack
	Seal at flange connection failed	S2	Deformation, corrosion	Leakage inside	II	B	Replace the seal
	Flange bolt break	S3	Corrosion	Leakage inside	II	D	Replace the bolt
Valve components	Butterfly spring failure	S4	Spring deformation, fracture	Leakage after close the valve	I	C	Replace the spring
	Valve plate damage	S5	Excessive wear and scratches	Leakage after close the valve	I	A	Welding repair
	Valve seat severely worn	S6	Excessive wear	Leakage after close the valve	I	B	Welding repair
	Valve seal failure	S7	Aging and pressure	Leakage after close the valve	I	B	Replace the seal
Hydraulic components	Cylinder crack	S8	Material or processing defects	Oil leakage inside	II	E	Repair the cylinder
	Damage inner cylinder	S9	Excessive wear and scratches	Oil leakage inside	II	D	Repair the cylinder
	Reset spring failure	S10	Material or processing defects lead to fracture, corrosion fracture	Cannot close automatically	I	D	Replace the spring
	Piston seal failure	S11	Sealing ring aging, pressure damage	Oil leakage inside	II	C	Replace the seal

	Stem thread failure	S12	Corrosion	Cannot close automatically	I	E	Repair the thread
	Piston stuck	S13	Deformation	Failed to open and shut	II	E	Replace the piston
	Stem packing seal failure	S14	Aging and excessive wear	May cause short downtime	I	C	Replace the stem packing

Table 13: FME analysis of components in safety valve.

4.5.2. CA (Criticality Analysis) for component

Based on the FMECA analysis tables above, the qualitative hazard matrix will be used to analyse the criticality for each equipment in the well control system. The x-axis in the matrix is the severity level of the failure mode, and the y-axis is the probability level of the failure mode. The failure mode code is marked in the corresponding position of the matrix with reference to its severity level and probability of occurrence, which can indicate the distribution of the hazards of each failure mode. This is to be able to distinguish which failure mode is the most harmful. Starting from the point of zero, the further the failure mode distribution point is from the origin along the diagonal direction, the more harmful the failure mode is, and the more attention should be paid on this failure mode.

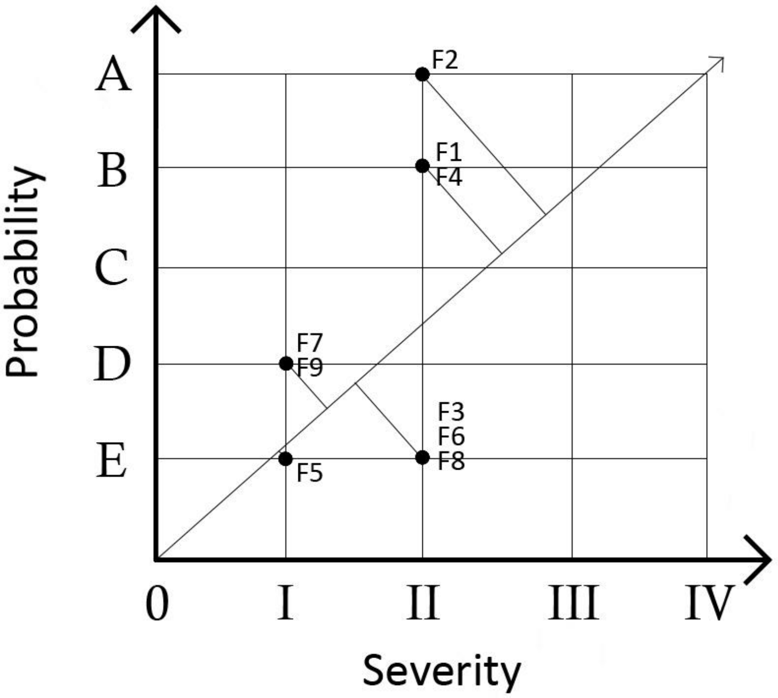

Figure 8: Hazard matrix for flex joint.

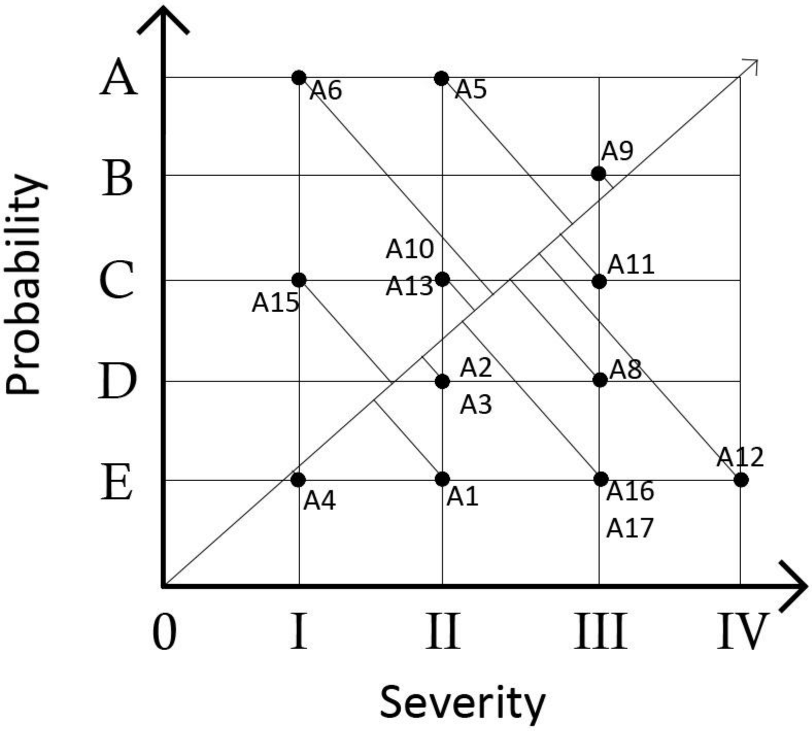

Figure 9: Hazard matrix for annular preventer.

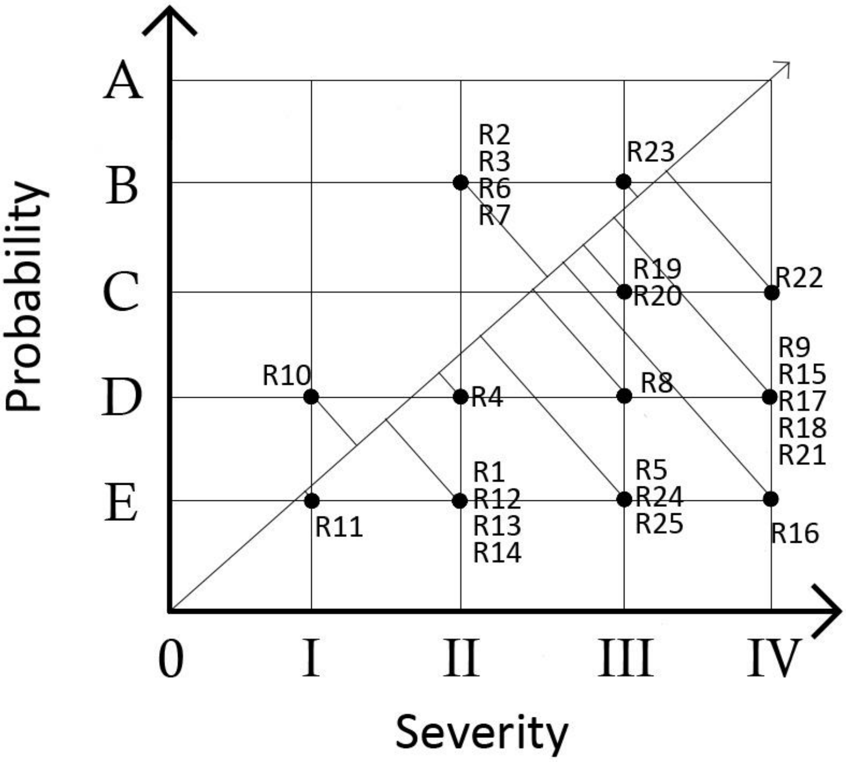

Figure 10: Hazard matrix for ram preventer.

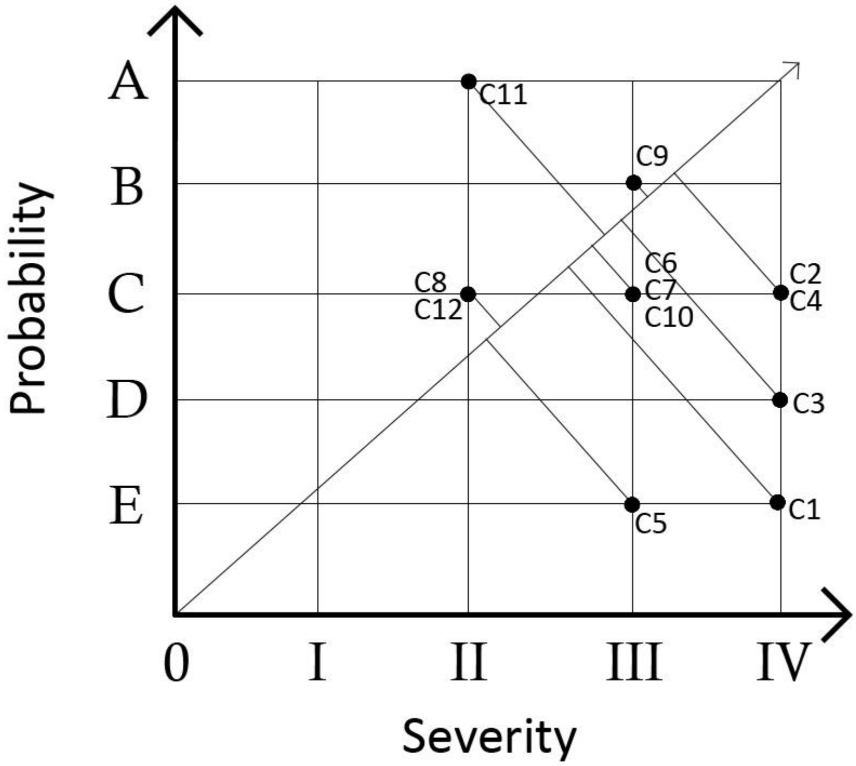

Figure 11: Hazard matrix for hydraulic connector.

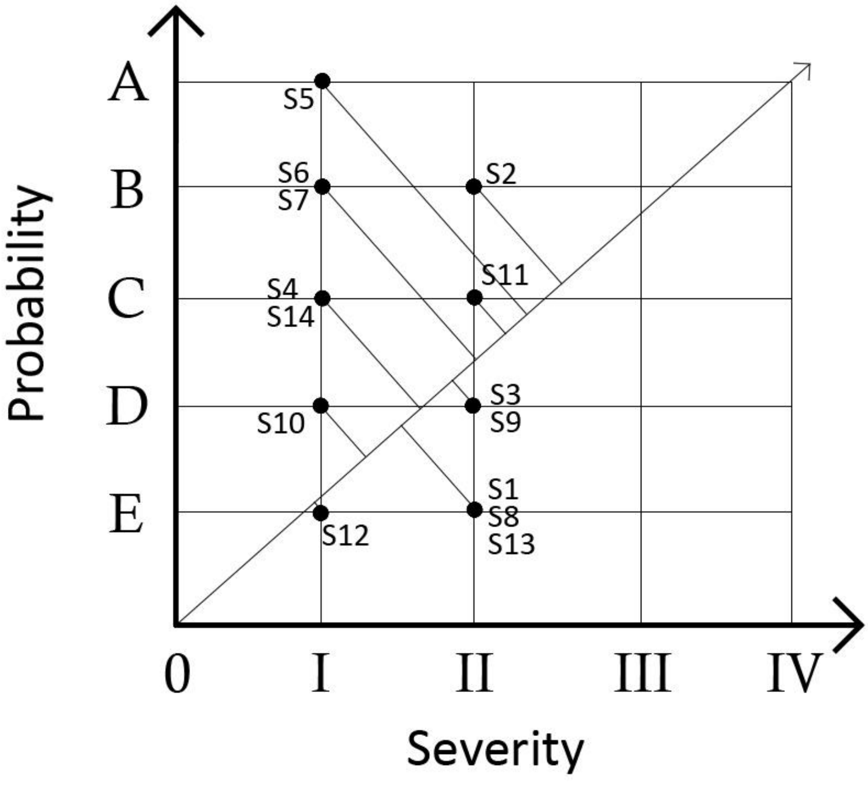

Figure 12: Hazard matrix for safety valve.

4.5.3. CA analysis conclusion

The following conclusions can be obtained from the CA hazard matrix:

(1) Flex joint

According to the analysis of the hazard matrix of the flexible joint, the failure modes F2 (Excessive wear on inner wear), F1 (Rubber failure), F4 (Sealing failure between spherical pressure ring and outer body) are the three failure modes with highest hazard degree.

These three failures will cause the relevant seals inside the flexible joint to fail, causing the medium in the well to leak into the sea from the point of failure. If the leakage is serious, it may cause the pressure in the well to be out of control and cause a blowout. The failure of the flexible joint may not lead to major accidents, but it often brings long downtime, environmental damages and huge economic losses.

(2) Annular preventer

The hazard matrix of the annular preventer shows that the three failure modes with the highest hazard degrees are A5 (Rubber core degumming and tearing), A9 (Piston sealing surface failure), and A6 (Rubber aging and deformation). Failure mode A5 and A6 are both rubber core failures, it should to be noted that the failure probability of rubber core failure of the annular preventer is related high, but because its failure consequences are not serious, many statistics do not even consider it as a failure, only as the normal use loss of the rubber core. In fact, the reason for the failure of the rubber core is not only the excessive wear in use, but also the improper operation and poor process are important factors.

The main reason for the failure of the piston seal is the aging, damage of the seal ring or the failure of the seal groove. The failure of the piston seal may cause channelling oil in the oil chamber of the liquid cylinder, resulting in a slow response or even inability to operate the BOP switch. The occurrence of this fault during a well inrush will seriously affect the response rate of shut in.

(3) Ram preventer

As the core equipment of the whole well control system, the ram preventer has many failure modes, and the overall failure hazard is high.

According to the analysis of the hazard matrix diagram of the ram preventer, the failure modes R23 (Wedge block at locking mechanism stuck) and R21 (Sealing failure of side door and piston rod) are the two most harmful failure modes. The other four failure modes R2 (Upper seal surface damage), R3 (Upper seal surface failure), R6 (Front ram seal failure), and R7 (Upper ram seal failure) also requires attention. Failure mode R23 (Wedge block at locking mechanism stuck) is a relatively common failure of a ram preventer. This fault is usually related to the deformation and corrosion of the wedge-shaped block. Even if the reaction force is too large after the shutter is closed, excessive friction may cause the fault. If this failure occurs during the locking process, the locking mechanism cannot lock the shutter in the closed state, and the shutter can only be kept closed by hydraulic pressure, and the oil circuit may be blocked for a long time. This failure occurs more often after locking. Although it will not cause a major accident, it usually brings a long downtime.

The failure of the side door bolt is the second most harmful in the failure of the ram BOP. This is mainly because the probability of occurrence of the fault is relatively high, and it is difficult to predict the consequences of the fault. The failure causes the side door to be not tightly sealed or even accidentally opened, which may cause the oil leakage and even a blowout in a worst case. It may also directly cause the gate to fail to close.

The four faults R2, R3, R6 and R7 are all seal failures. These failure modes may not bring serious accidents, but the probability of failure is relatively high and should be paid attention to.

(4) Hydraulic connector

The hydraulic connector is a key device in the entire system, and its failure may cause the most serious consequences. The reliability of the hydraulic connector also needs to pay attention to in the entire system. Failure modes H11 (Metal seal failure) and H9 (Damage inner the cylinder) are the two most dangerous failure modes among hydraulic connector failures.

The metal sealing ring refers to the seal installed between the hydraulic connector and the wellhead. Its failure usually leads to external leakage of the medium in the well. The cause of this failure is related to the characteristics of the metal sealing ring itself, or it may be caused by improper installation and use. The probability of failure is high and should be taken seriously. Damage to the inner wall of the cylinder is a failure mode that may lead to serious consequences. Due to excessive wear caused by long-term use or impurities in the hydraulic oil, it may scratch the inner wall of the cylinder, causing oil leakage inside the cylinder. To repair this failure usually takes a long time and should be discovered in time in the future for maintenance to avoid huge losses.

(5) Accident safety valve

In general, the failure hazard of accident safety valves is much lower than other equipment. The failure of the accident safety valve does not directly lead to the failure of shutting the well, and because the redundancy setting is usually adopted, the possibility of this failure causing extra maintenance is greatly reduced. It can be seen from the hazard matrix of the accident safety valve that the failure modes S5 (Valve plate damage) and S2 (Seal at flange connection failed) are the top two hazards. In the case of long-term use of the sealing surface of the valve plate, it is normal to have excessive wear of the seal ring, which leads to an excessively large sealing gap and a poor safety valve sealing. In addition, impurities and debris in the drilling fluid scratching the valve plate are also an important reason of the valve failure.

The probability of this failure is related high, but it will not cause much harm. The failure of the seal at the flange connection is another common failure and it often leads to oil leakage and in serious cases, it may cause a blowout.

5. Bow-Tie Analysis of BOP

5.1. Bow-Tie Method

The bow-tie method is a modelling method that combines the fault tree analysis (FTA) and the event tree analysis (ETA) to analyse the causes, accident consequences, accident prevention and control of the accident. KHAN constructed and used offshore well control bowtie model and Bayesian method to realize the risk analysis of oil and gas well drilling operations [38].

The FTA analysis method is a graphical deductive reasoning method. Through qualitative and quantitative analysis, the main cause of the accident can be found out, which provides a reliable basis for analysing the cause of the accident and determining the safety countermeasures. The ETA analysis method starts from the initial state of the accident, uses logical reasoning, and analyses the process from the cause of the accident to the result according to the development order of time. Through ETA, various accident consequences that may occur in a complex system can be predicted.

5.2. FTA Analysis

5.2.1. FTA process

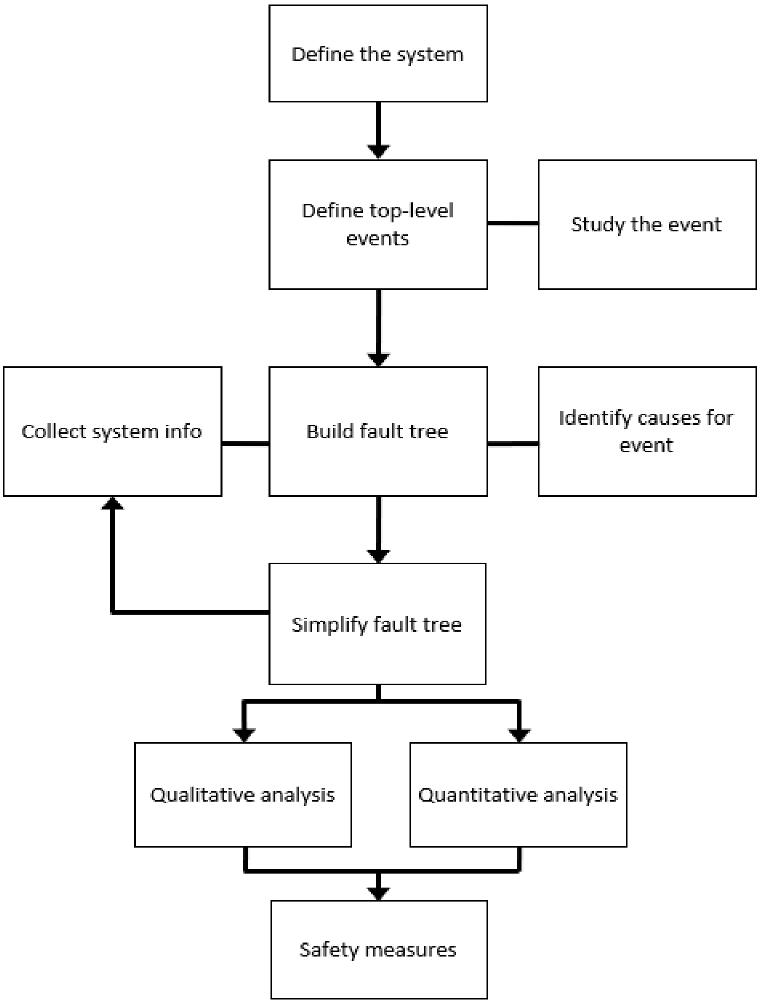

Figure 13: FTA process.

The FTA process is shown on figure above and here is a short description of different steps [39]:

(1) Understand the system structure and specific parameters; clarify its working environment, tasks and lifetime profile.

(2) Identify the failures of the system, by collecting real time data, including failure statistics of similar systems or equipment, combined with the system structure and function analysis, to find out the failures that have occurred in the system earlier and those that potentially would happen. Investigate all possible causes of failures and other complex factors, including:

- Mechanical equipment failure
- Material defects and processing technology factors
- Environments, complex working conditions,
- Failures in operations and transportation
- Failures in daily maintenance, etc.

(3) Select the top event of the fault tree that is the most undesirable situation in the system. According to the investigation results of the system failure, combined with the FMECA conclusion, the events with serious failure consequences and high failure probability are selected as the top events of the fault tree.

(4) The core of fault tree analysis is to build the fault tree. After the above preparation are fully done, start from the top event, find out all the direct cause events that lead to the top event, and go through from top to bottom until all the cause events are basic events. According to the logical relationship, use the logic gate to connect the upper and lower events to draw the fault tree.

(5) Qualitative and quantitative analysis of the fault tree. List the minimum cut set and minimum path set of the fault tree, find the structure and probability of each bottom event.

(6) The purpose of building a fault tree is to find and eliminate hidden risks, find defects in the design and manufacture of the system and errors occur during operation, then standardize all the failures and try to improve them. After a comprehensive analysis of the fault tree, safety measures should be implemented to reduce the risk.

5.2.2. Determine top event

According to the calculation results of the damage degree of each failure mode in Chapter 4, all the failure modes with category IV and failure modes with high harmful degree in category II and III failures are selected as the top event of the failure tree. For failure modes with similar failure types, select a representative one for analysis.

Therefore, the top events of the fault tree analysis in this section are determined as: ‘hydraulic connector unlock failure’, ‘gate blowout preventer closing failure’, ‘annular preventer closing failure’, ‘gate blowout preventer unlocking failure’, ‘gate blowout preventer sealing failure’ and ‘annular preventers are not well sealed’.

5.2.3. Symbols in FTA

There are many symbols used in FTA, here are some of the symbols used in this thesis and some of their descriptions.

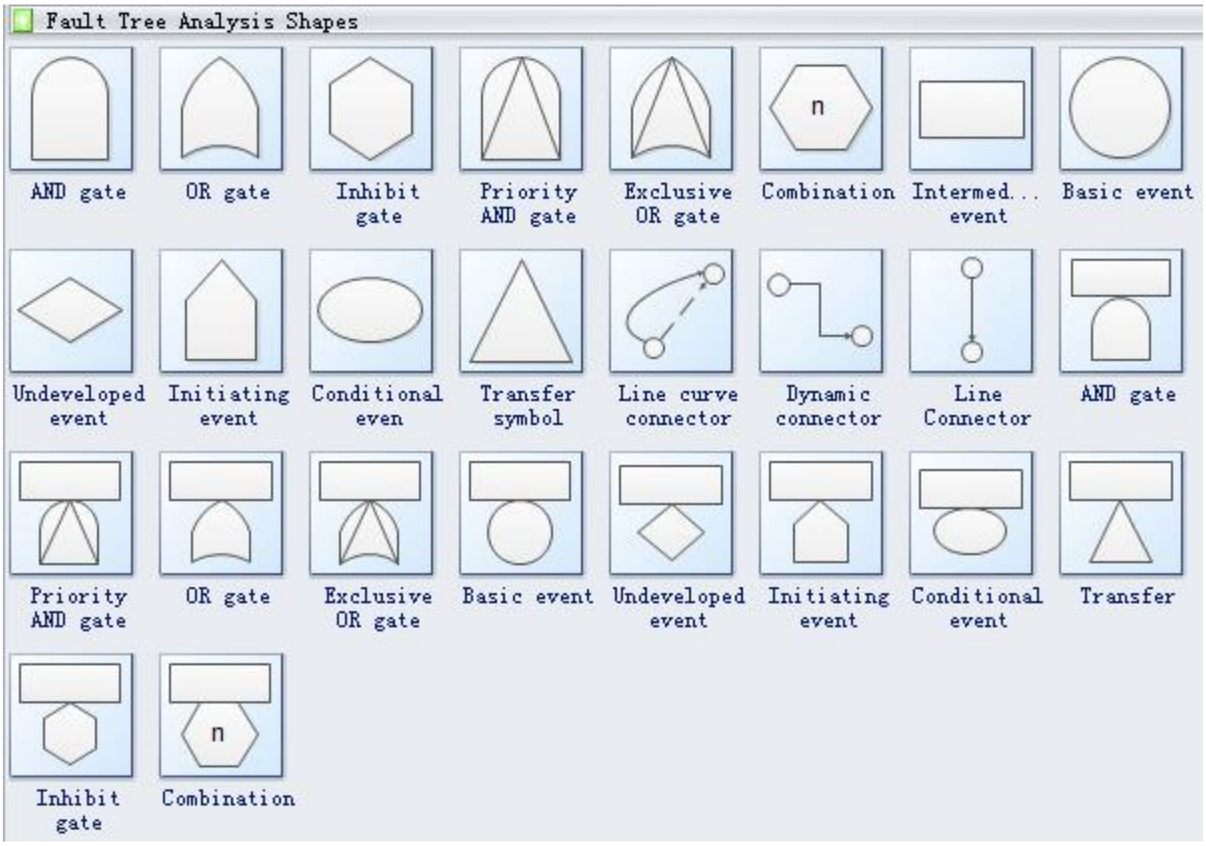

Figure 14: FTA symbols.

OR gate - An event occurs if at least one of the input events takes place.

AND gate - An event occurs only if all input conditions are met.

Basic event - failure or error in a system component or element.

Transfer symbol - used to connect the inputs and outputs of related fault trees.

5.2.4. FTA of Hydraulic connector unlock failure

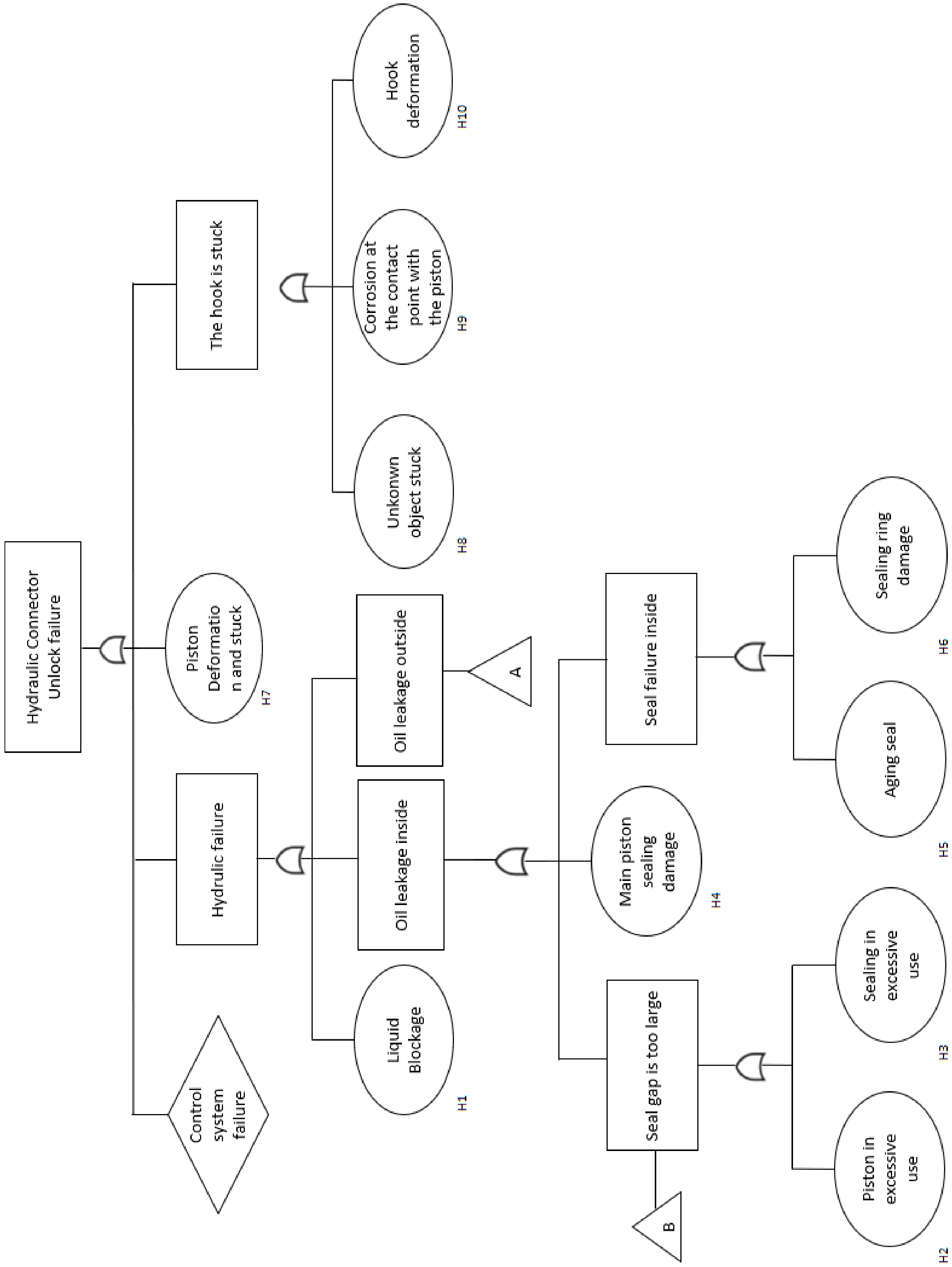

Figure 15: FTA of Hydraulic connector unlock failure (1).

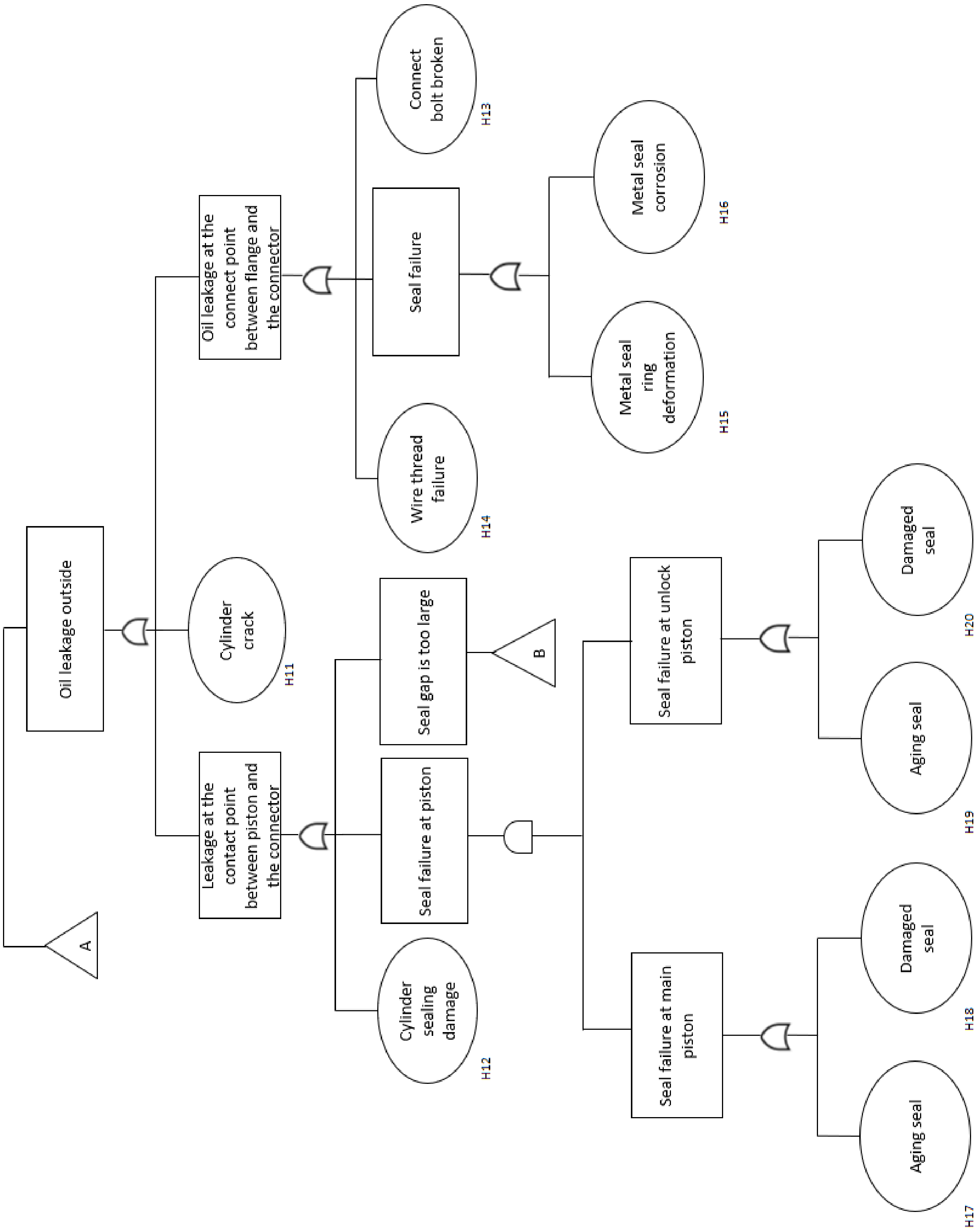

Figure 16: FTA of Hydraulic connector unlock failure (2).

The minimum cut set of the fault tree is: {H17 H19}; {H17 H20}; {H18 H19}; {H18 H20}; {H1}; {H2}; {H3}; {H4}; {H5}; {H6}; {H7}; {H8}; {H9}; {H10}; {H11}; {H12}; {H13}; {H14}; {H15}; {H16}.

The minimum path set of the fault tree is: {H2 H9 H8 H1 H10 H11 H16 H13 H14 H15 H6 H5 H18 H12 H17 H7 H3 H4 H19}; {H2 H9 H8 H1 H10 H11 H16 H13 H14 H15 H6 H5 H20 H12 H17 H7 H3 H4 H21}.

Without considering the occurrence probability of the basic event, there are 16 minimum cut sets with single basic event in this fault tree, and these 16 basic events are more important than the minimum cut sets with two basic events. The excessive wear of pistons and cylinders are common failure of hydraulic equipment. It can be repaired by spraying or electroplating. It should be checked and maintained regularly.

The failure of the control system is more complicated. Due to the lack of relevant information, detailed analysis is not performed here. It is only listed as an undetected event. It can be supplemented when more data is obtained in the future.

5.2.5. FTA of Ram preventer shut-off failure

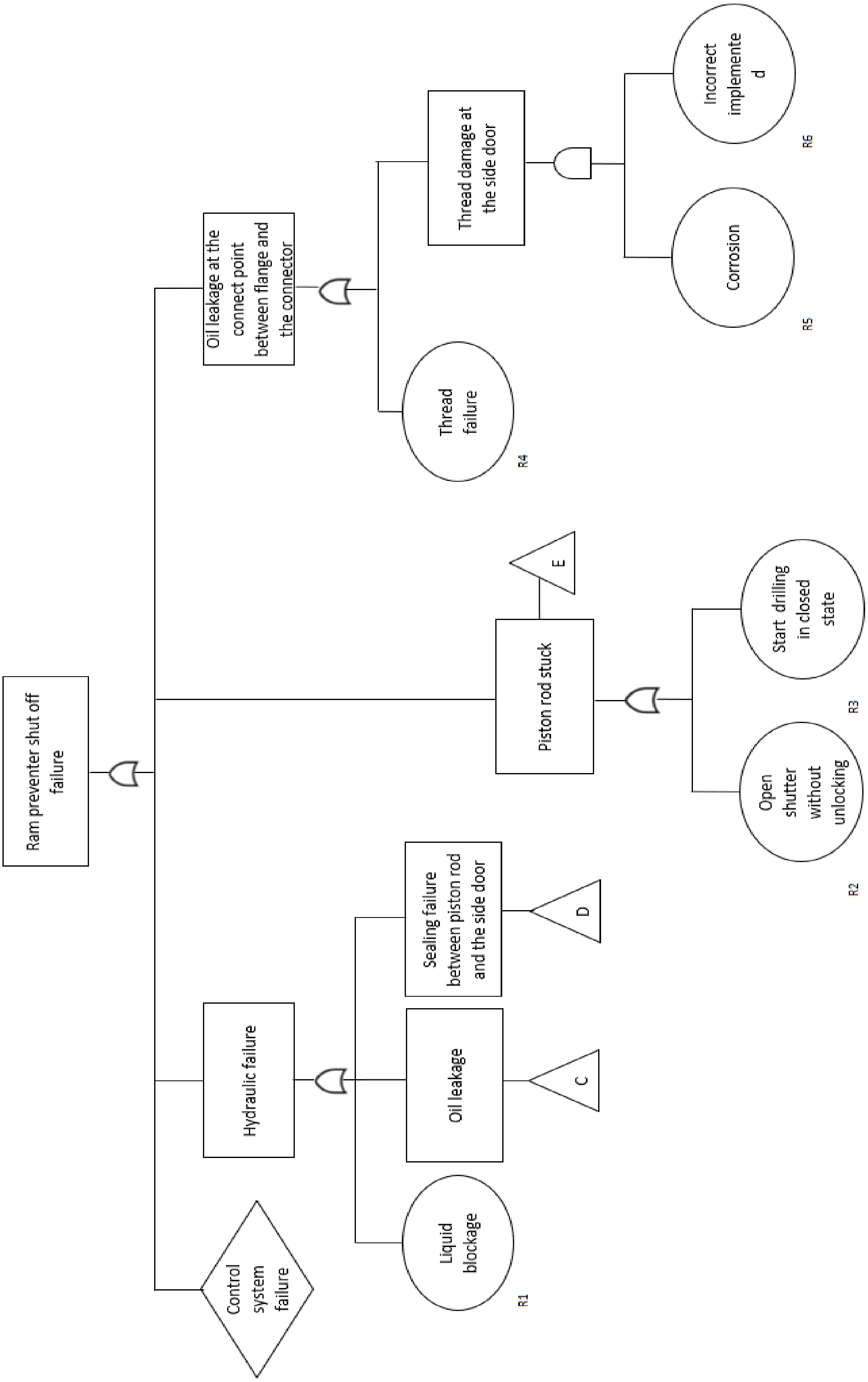

Figure 17: FTA of ram preventer shut off failure (1).

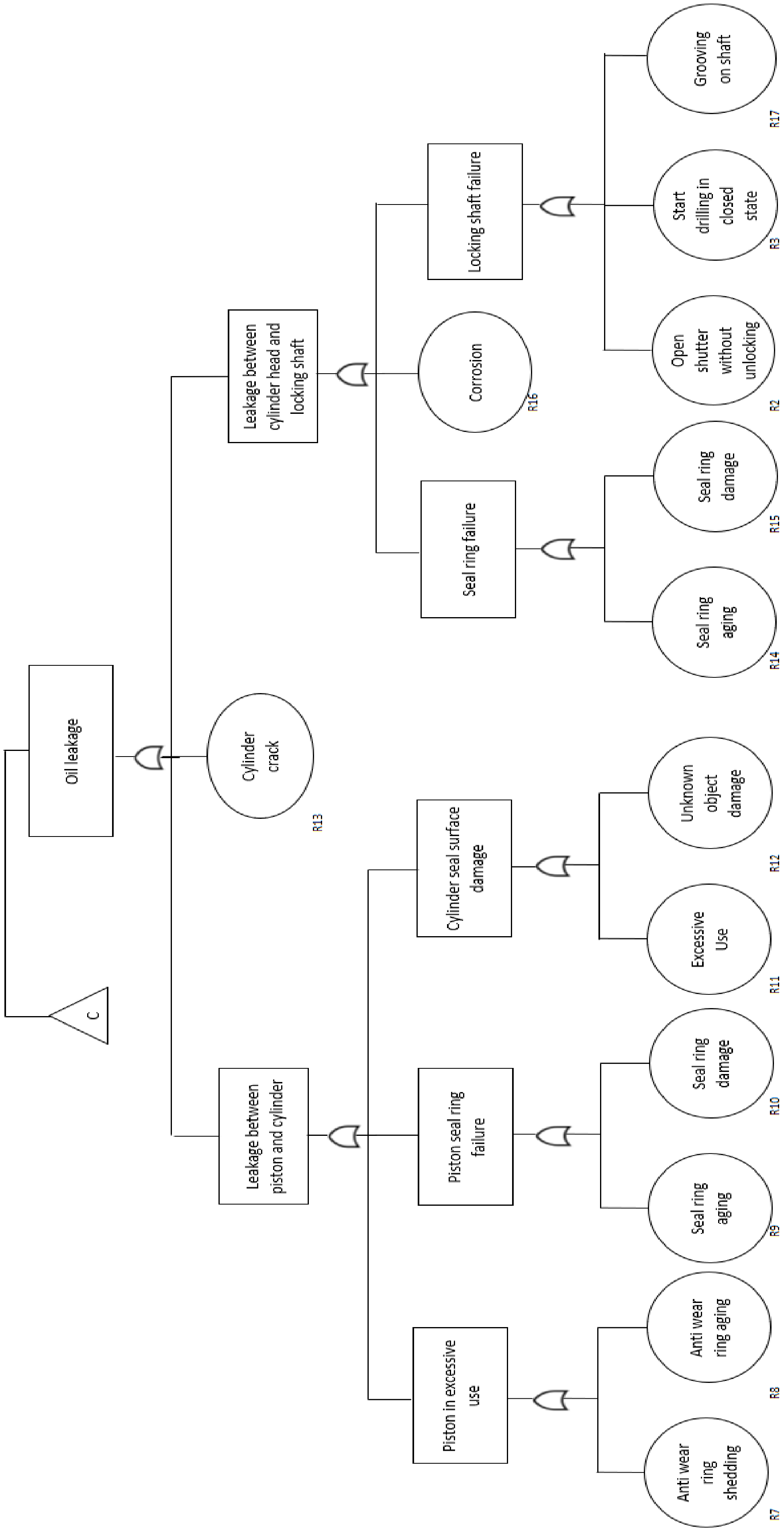

Figure 18: FTA of ram preventer shut off failure (2).

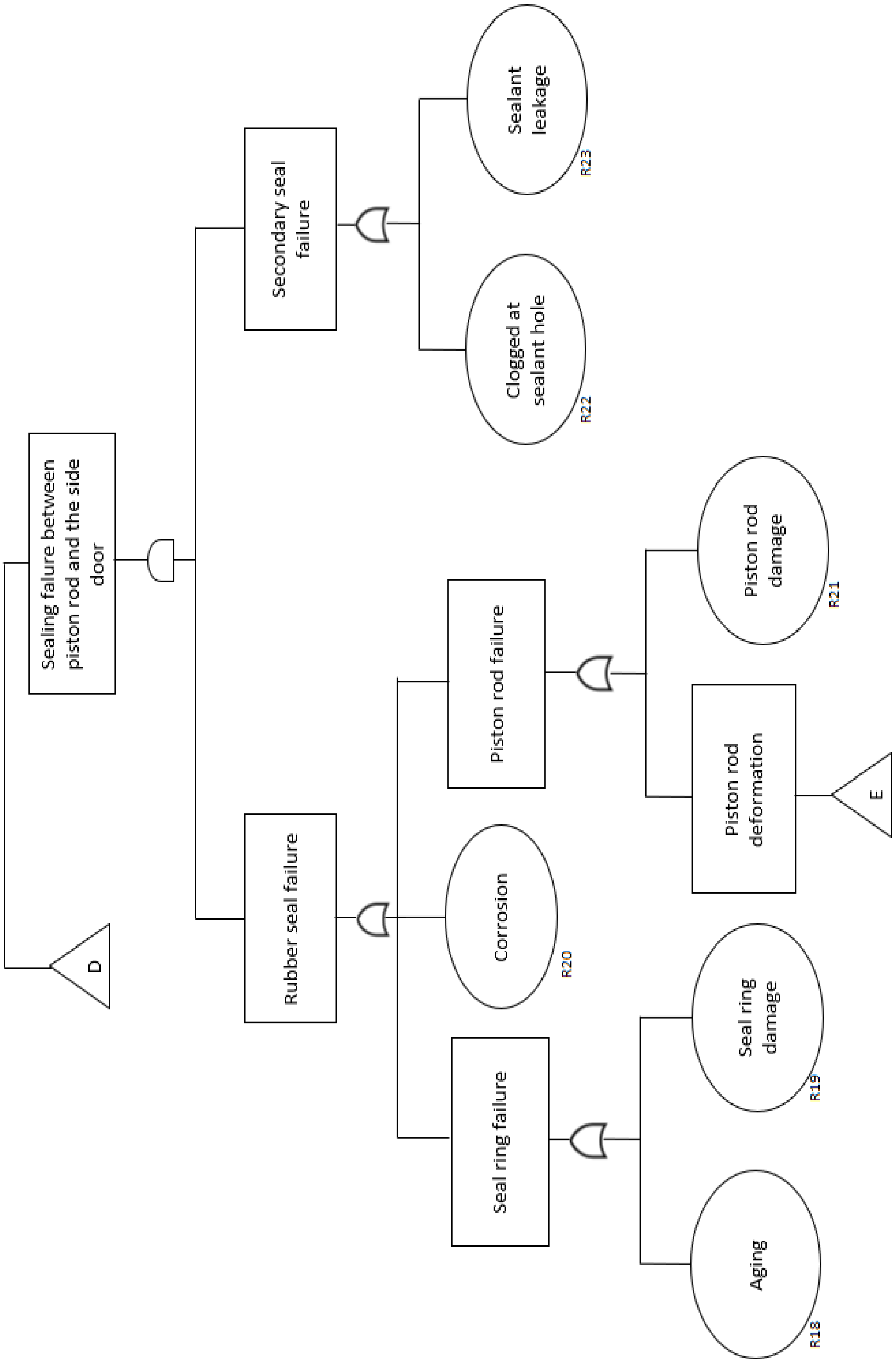

Figure 19: FTA of ram preventer shut off failure (3).

The minimum cut set of the fault tree is: {R5 R6}; {R18 R22}; {R18 R23}; {R21 R23}; {R20 R23}; {R20 R22}; {R19 R23}; {R21 R22}; {R19 R22}; {R15}; {R10}; {R12}; {R8}; {R1}; {R4 }; {R7}; {R16}; {R17}; {R9}; {R11}; {R2}{R14}; {R13}; {R3}.

The minimum path set of the fault tree is: {R7 R2 R5 R18 R1 R4 R14 R13 R3 R20 R16 R21 R17 R9 R11 R19 R15 R10 R12 R8}; {R7 R2 R5 R22 R1 R4 R14 R13 R3 R23 R16 R17 R9 R11 R15 R10 R12 R8}; {R7 R2 R6 R22 R1 R4 R14 R13 R3 R9 R11 R23 R16 R10 R12 R17 R8 R15}; {R7 R2 R6 R18 R1 R4 R14 R13 R3 R9 R11 R20 R16 R10 R12 R21 R17 R8 R19 R15}.

Through fault tree analysis, it is found that the cause of the shut-off failure is more complicated. The hydraulic failure caused by seal failure is an important one. From the perspective of structural importance, the most important part to take attention is the secondary seal between the piston rod and the side door. In addition, the deformation of the piston rod due to mechanical impact may cause damage to the ram and may also cause the seal failure. Therefore, the deformation of the piston rod due to improper operation should be avoided as far as possible under installation and operation.

5.2.6. FTA of Annual preventer shut-off failure

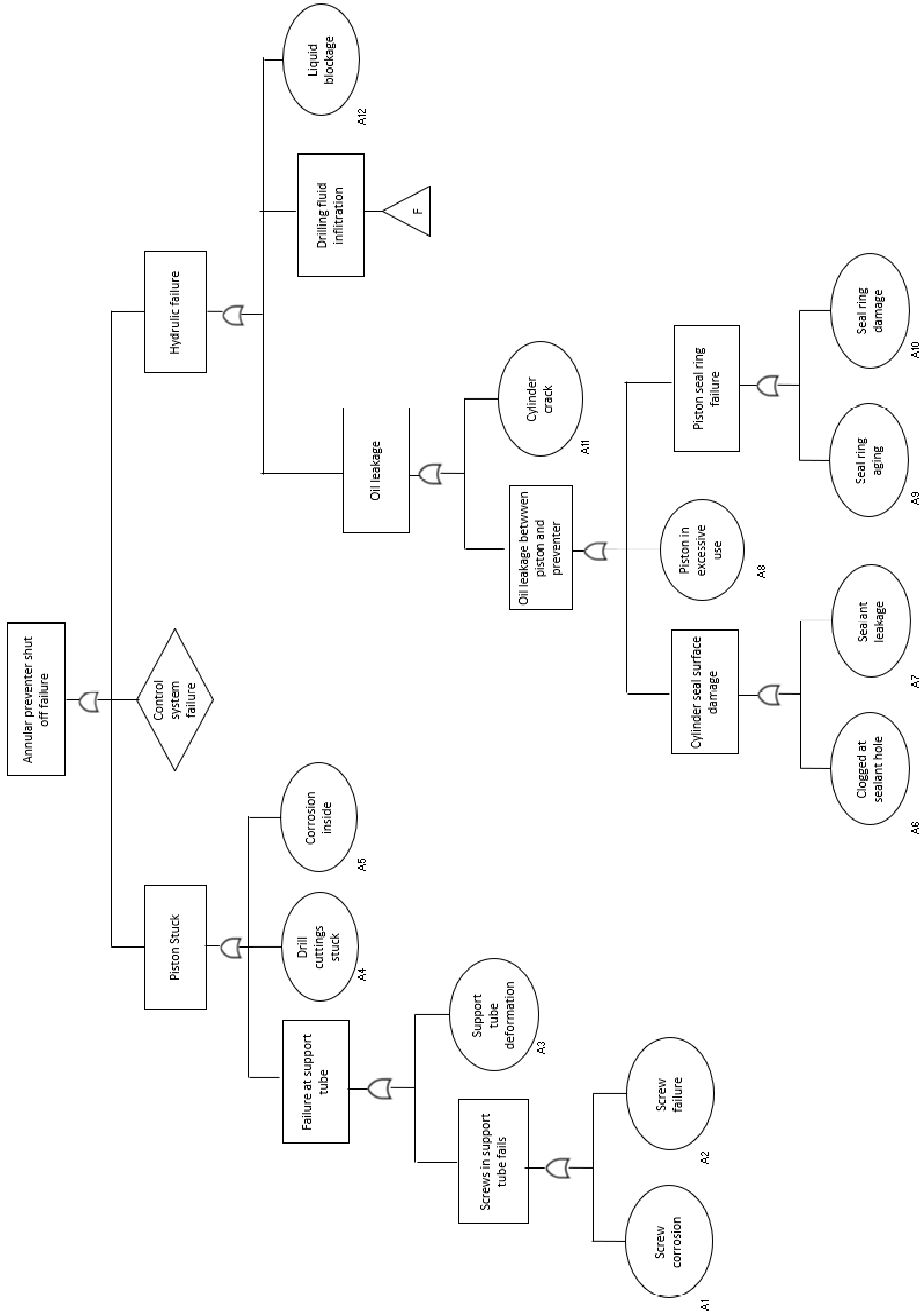

Figure 20: FTA of Annual preventer shut-off failure (1).

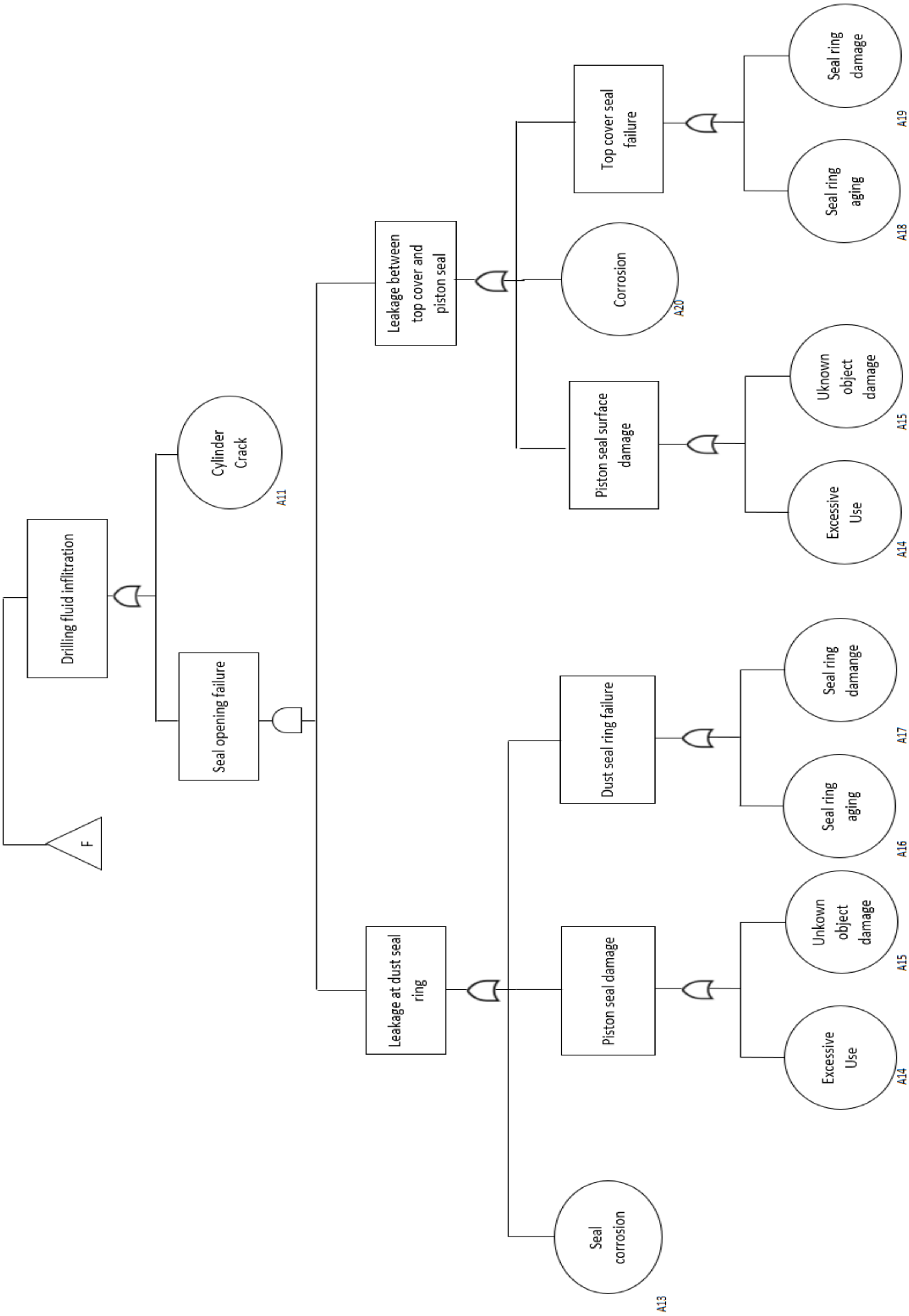

Figure 21: FTA of Annual preventer shut-off failure (2).

The minimum cut set of the fault tree is:

{A16 A18}; {A13 A18}; {A16 A20}; {A13 A20}; {A17 A18}; {A16 A19}; {A13A19}; {A17 A20}; {A17 A19}; {A1}; {A2}; {A3}; {A4}; {A5}; {A6}; {A7}; {A8}; {A9}; {A10}; {A11}; {A12}; {A14}; {A15}.

The minimum path set of the accident tree is:

{A1 A6 A4 A5 A14 A12 A11 A3 A2 A9 A8 A16 A13 A10 A17 A7 A15}; {A1 A6 A4 A5 A14 A12 A11 A3 A2 A9 A8 A18 A13 A10 A19 A7 A15}.

During the use of annual preventer, attention should be paid to the replacement and maintenance of vulnerable parts. It is also recommended to improve the design of the piston in annular preventer, reduce the wear of the sealing surface of the piston and in the cylinder, and extend the lifetime.

5.2.7. FTA of Ram preventer unlock failure

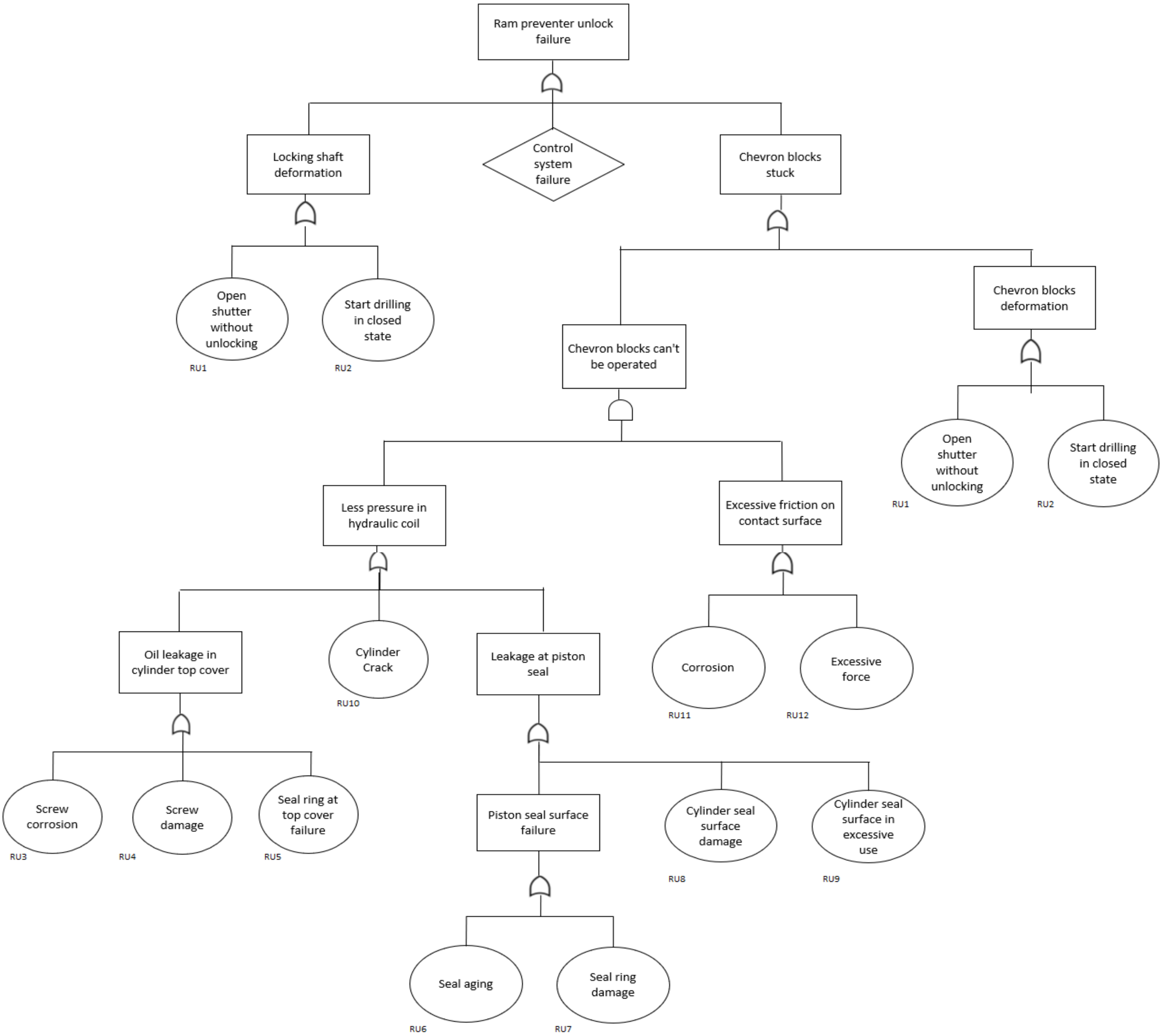

Figure 22: FTA of Ram preventer unlock failure.

The minimum cut set of this fault tree is: {RU3 RU11}; {RU3 RU12}; {RU6 RU12}; {RU10 RU12}; {RU8 RU12}; {RU9 RU12}; {RU6 RU11}; {RU10 RU11}; {RU4 RU12}; {RU5 RU12}; {RU7 RU12}; {RU8 RU11}; {RU9 RU11}; {RU4 RU11}; {RU5 RU11}; {RU7 RU11}; {RU1}; {RU2};

The minimum path set of this fault tree is: {RU1 RU3 RU2 RU6 RU10 RU8 RU9 RU4 RU5 RU7}; {RU1 RU11 RU2 RU12}.

Analysis of the fault tree shows that events RU1 and RU2 should be paid attention at first. These two basic events are usually caused by the operators who have not strictly followed the procedures in operation. Considering the overall probability of failure, the corrosion of the wedge-shaped surface of the locking block is a more serious failure mode. Due to the occurrence of pitting, the friction of the contact surface will usually increase, and the locking mechanism will get stuck.

5.2.8. FTA of leakage inside ram preventer failure

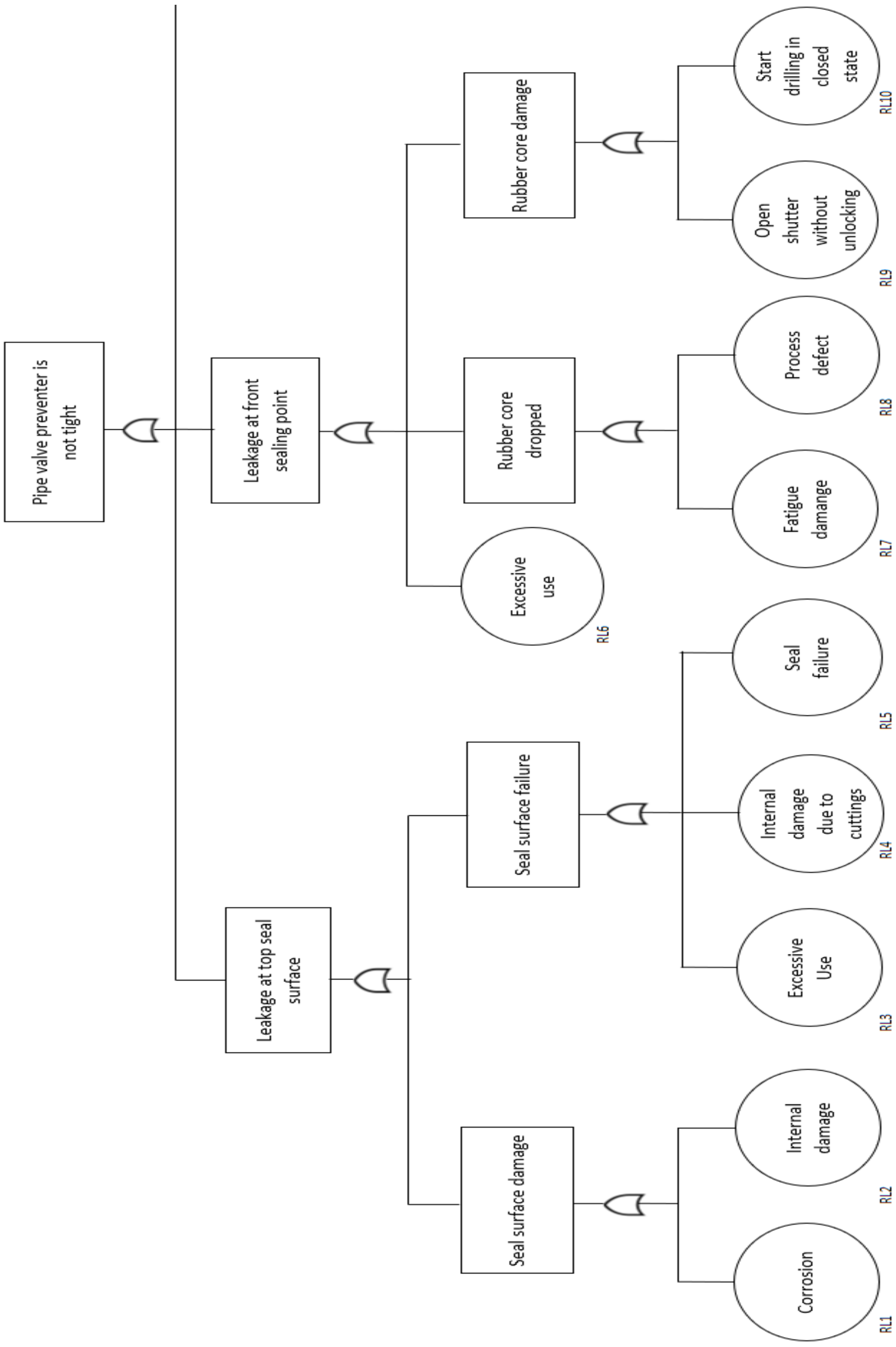

Figure 23: FTA of leakage inside ram preventer failure (left side).

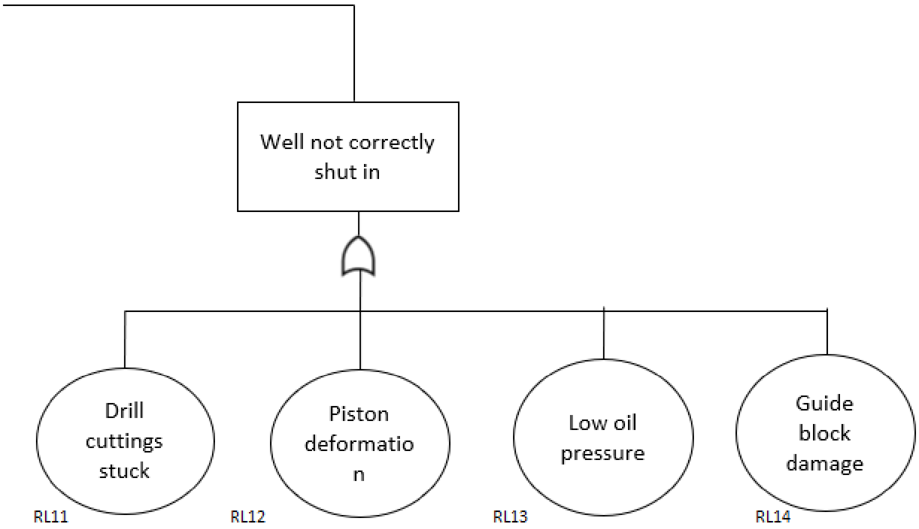

Figure 24: FTA of leakage inside ram preventer failure (right side).

This fault tree is a total OR gate structure, so each of the basic event has equal importance, and each basic event is separately considering as a minimum cut set. Here we should also pay more attention to the failure caused by improper operation. In addition, from the perspective of the failure probability, the failure of rubber cores is the main reason for the inadequate sealing. Improving the material and vulcanization process of the rubber core can effectively reduce the loss caused by core failure.

5.2.9. FTA of leakage inside annual preventer failure

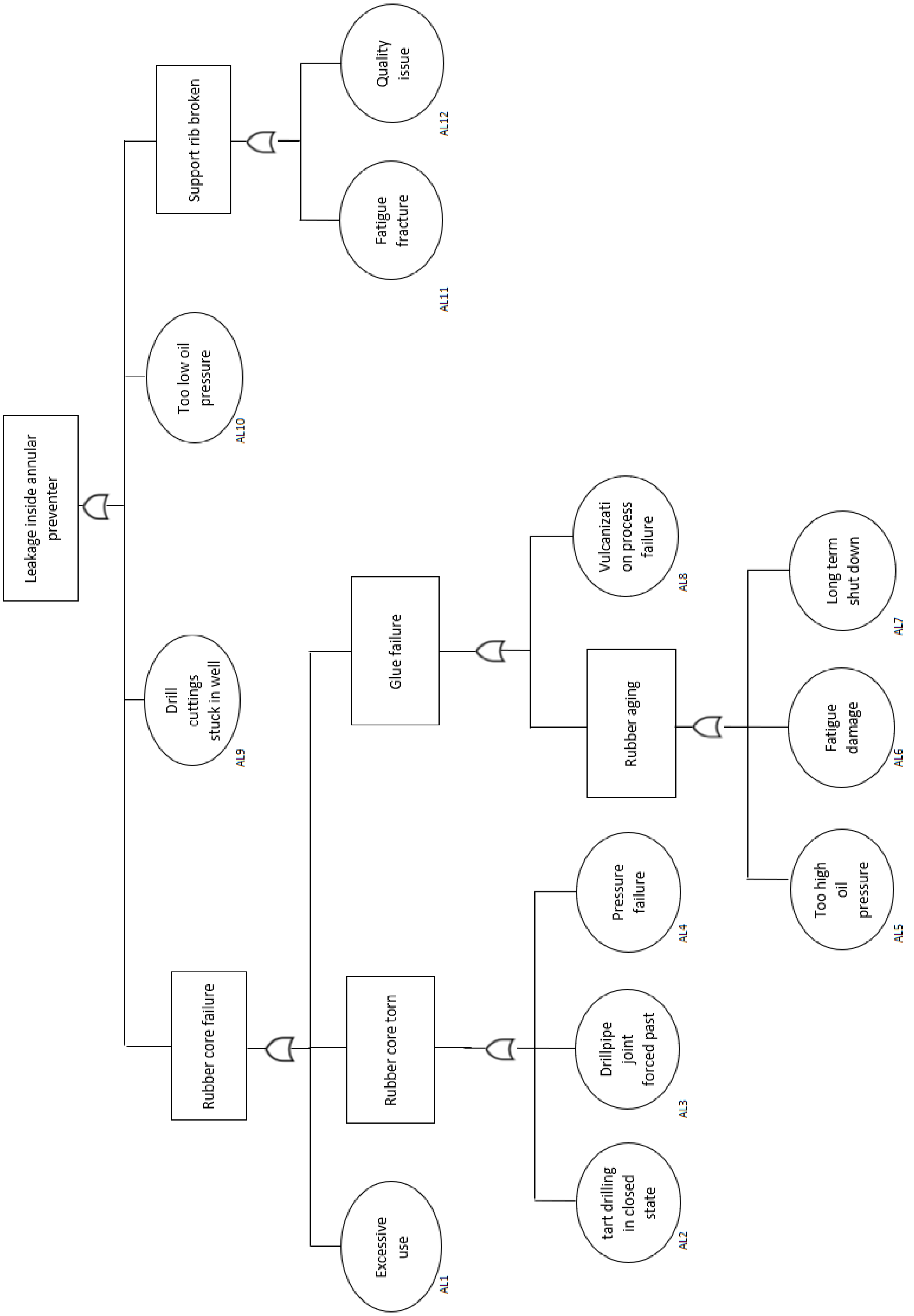

Figure 25: FTA of leakage inside annular preventer failure.

This fault tree is also a total OR gate structure, so the importance of each basic event is equal, and each bottom event constitutes a minimum cut set separately. It is difficult to define the failure reason of the annular preventer sealing. When the hydraulic oil pressure is slightly lower, there may be a few overflows of mud between the rubber core and the drill pipe, in this case, it is still reliable to seal the well. The sealing failure discussed here mainly refers to the situation of a large amount of mud overflow caused by the failure of the rubber core.

5.3. ETA Analysis

Based on Bow-Tie example Figure 1 in chapter 1.3.2, the Bow-Tie model diagram for the BOP system can be drawn as:

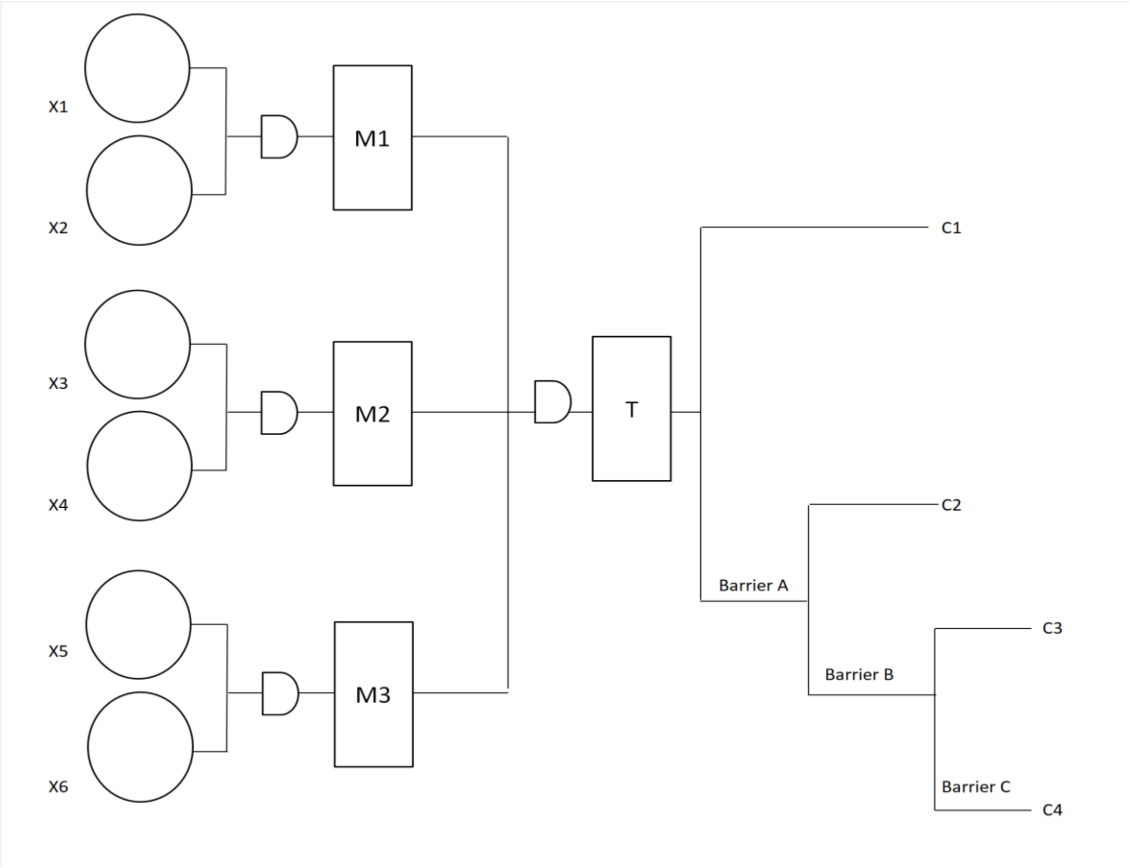

Figure 26: Bow-Tie model diagram.

The left side of the model is the FTA analysis, which is implemented in Chapter 5.2, the right side of the model is the event tree analysis (ETA), where C_1-C_4 represents different consequences causes by different events.

After the blowout preventer system failure, the failure of the well control might cause a blowout. Fire prevention is the primary focus when blowout happens, so the fire prevention barrier is taken as the first safety barrier. If the fire prevention barrier fails, once a fire or explosion occurs, the fire and explosion suppression devices on the platform must be immediately activated as a secondary prevention and control barrier to suppress the spread of fire and prevent more serious explosion accidents. When both the previous two safety barrier failed, the emergency management barrier becomes the last safety barrier to protect the personal safety. The barrier includes emergency evacuation alarms, emergency evacuation devices, emergency escape training, and emergency rescue systems [40].

The event tree of BOP system can be drawn as:

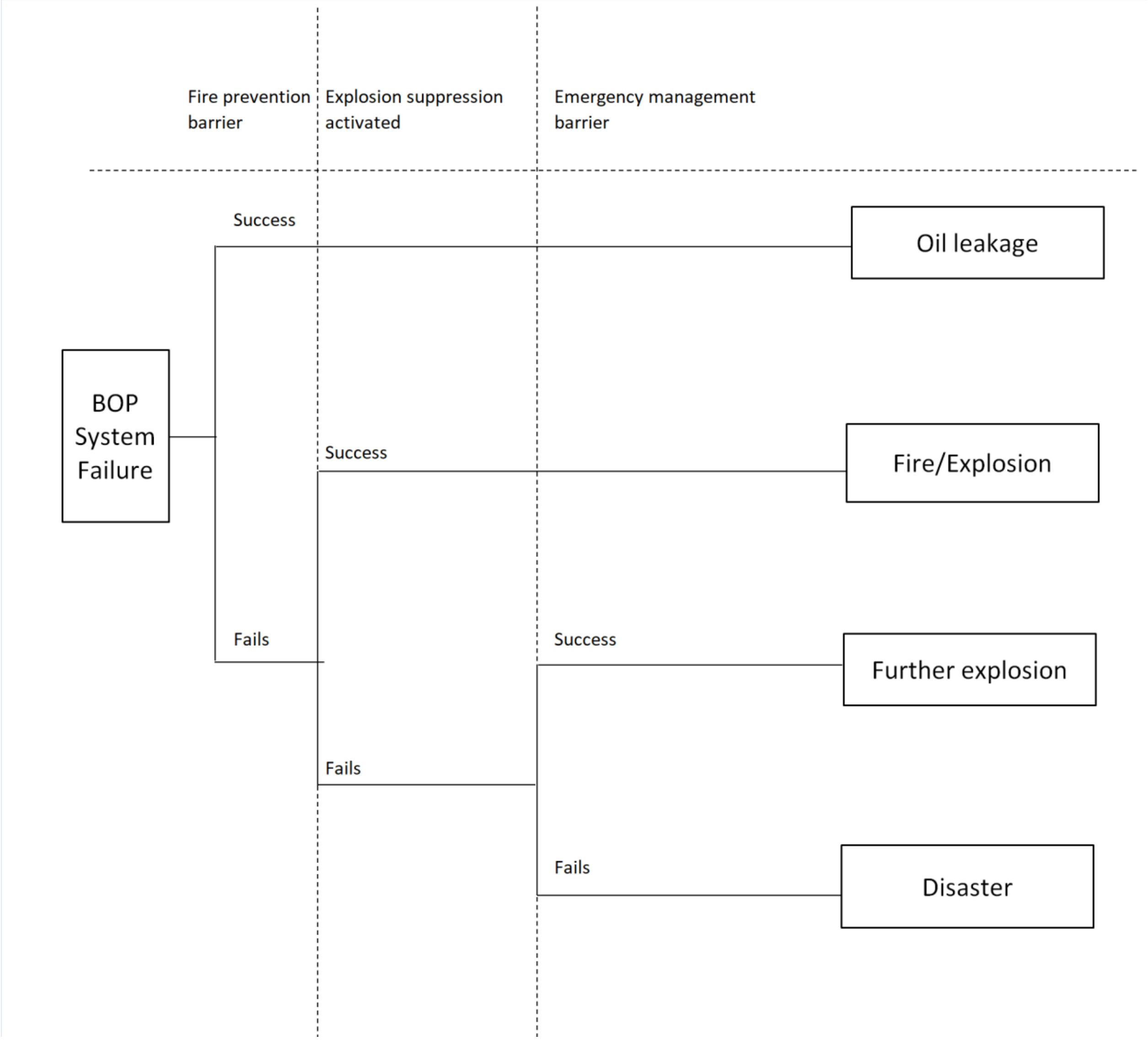

Figure 27: The event tree diagram.

The probability of each consequences can be calculated, $C_1 – C_4$ refers to consequences 1 to 4, and A, B, C refers to barriers A, B and C from Figure 26:

$P(C_1) = (1-P(A)) \times P(T)$

$P(C_2) = P(A) \times (1 – P(B)) X P(T)$

$P(C_3) = P(A) \times P(B) \times (1- P(C)) \times P(T)$

$P(C_4) = P(A) \times P(B) \times P(C) \times P(T)$

5.4. Bow-Tie model of BOP

In this chapter, failure mode 'Leakage inside annual preventer failure' from Chapter 5.2.9 will be taken as the left side of the Bow-Tie model. And the Bow-Tie model can be built combined with the ETA from Figure 27, AL 1 – AL 12 refers to the 12 basic events in the failure mode, T is the top event, $C_1 – C_4$ refers to different consequences:

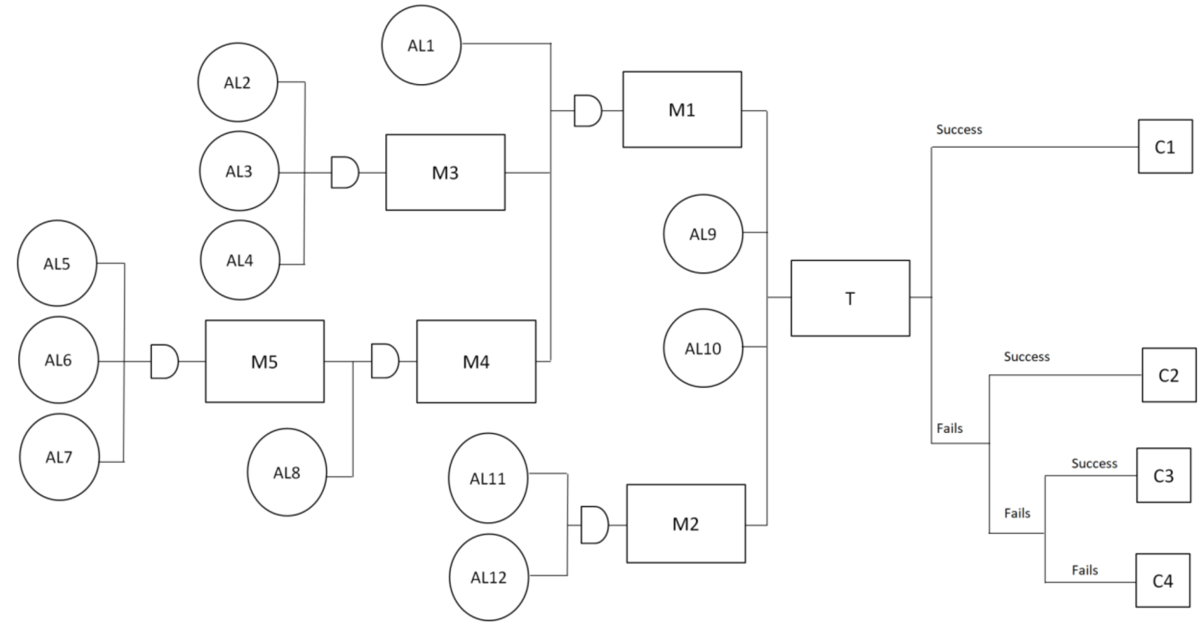

Figure 28: A Bow-Tie model of BOP system.

Since this failure mode is an all OR-gate fault tree, the probability of top event will be:
P(T) = P (AL1 + AL2 + AL3 + AL4+ AL5 + AL6+ AL7 + AL8+ AL9 + AL10+ AL11 + AL12)

And then the probabilities of consequences can be calculated form formulas in previous Chapter 5.3. This method can used on all failure modes in Chapter 4 for consequences probability calculations. [41]

5.5. Conclusion of analysis

The failure of mechanical equipment is different from that of electronic equipment. Various failure factors are not irrelevant but interact.

Usually a failure may cause other forms of failure, and the failure of a certain component is often the result of a combination of factors. [27]

Through the comprehensive analysis of FMECA and FTA, the failure modes or causes leading to system failure are summarized and summarized, mainly in the following aspects:

(1) Corrosion Failure

The working environment of the blowout preventer unit is at the bottom of a thousand meters deep. The high-speed fluid in the well is also corrosive to the equipment. The analysis of the fault tree shows that corrosion failure is an important cause of system failure. For example, the corrosion of the sealing groove leads to the failure of the sealing of the hydraulic component. This fault has appeared in several fault trees.

Corrosion failures often work together with other forms of failure, causing more serious failures. For example, pitting corrosion usually occurs on the sealing surface of the ram cavity, causing leakage of the top seal of the ram, and due to the contact movement of the surface of the ram and the upper sealing surface, corrosion and wear will also occur. The contact movement will wear away the compound formed by the corroded surface, and the exposed fresh surface will be quickly worn away by the corrosion. Corrosion accelerates wear, which in turn aggravates corrosion and accelerates the rate of corrosion. Therefore, for similar surfaces with relative contact movement in the equipment, anti-corrosion treatment should be strengthened, the surface treatment process should be improved, and the surface should be improved.

The delayed fracture of the side door bolt of the ram BOP due to stress corrosion damage is also a typical case of the combination of corrosion failure and other failure forms. Stress corrosion damage is the phenomenon of metal fracture caused by the synergistic effect of stress and chemical media. It is caused by the continuous tensile stress and chemical erosion that causes cracks and expansion of metal parts. In order to avoid this type of failure, it is recommended to perform Cd-Ti electroplating on the surface of the bolt, which can not only prevent stress corrosion cracking, but also avoid hydrogen fracture caused by electroplating.

(2) Wear failure

Wear failure is another major cause of BOP failure. Most of the equipment in the system is hydraulically operated, and it often happens that the seal gap is too large due to the wear of the liquid cylinder and the piston, and hydraulic oil leakage occurs. With the increase of use time, the probability of such failure increases. In order to avoid failures due to wear failure as much as possible, the regular maintenance system of the equipment should be strict to detect and deal with excessive wear in time; In addition, the design and processing technology should be improved to improve the wear resistance of the components, such as adding on the piston of the annular blowout preventer Installing a wear ring can slow down the wear rate of the piston to a great extent.

Wear of the rubber core is another important aspect of the failure caused by the wear of the blowout preventer . Due to the high-speed erosion of drilling fluid for a long time and the movement of the drill pipe after the well is sealed, wear and tear failure is the main reason for the failure of the BOP rubber core. Rubber core wear is a normal loss of equipment. In the case of normal equipment maintenance and timely replacement of components, rubber core wear will not cause too much harm. However, to avoid artificial improper operation to accelerate the wear rate, it is strictly forbidden to turn the drilling tool when the well is closed and try not to lower the drilling tool. If necessary, the closing pressure of the blowout preventer should be well controlled to reduce the rubber core from the drilling.

(3) Seal failure

Seal failure is the most common form of failure in hydraulic equipment. For the rubber seals in the equipment, aging makes it the most important cause of failure. Every time the equipment is overhauled, all rubber seals are usually replaced, so the actual use time of the sealing ring is not long. However, due to improper storage and storage measures by users, such as hanging seals and storage locations close to heat sources, the aging of the seal is usually accelerated. In addition, users can directly install the aging and deformation of the rubber ring during installation, which is an important reason for the failure of the system due to aging of the seal, it is also important to comply with the storage and use system of the sealing ring.

The excessive wear and breakage of seals are also causing of system failure. Improper operation during the installation may cause damage to the seals, particles in hydraulic oil may also damage the seals, and further damage to the sealing surface of the piston or cylinder, in addition, improper selection of the material and hardness of the seal ring could cause shear tearing failures.

In another hand, corrosion may also indirectly lead to seal failure. The most typical example is the seal at the piston rod of the ram preventer. Due to the corrosion damage of the retaining ring groove, the retaining ring and the sealing ring were washed away by the liquid inside the well, and many seal failures would occur.

The leakage at the flange connection is the main form of external leakage in the system, metal rings are usually in use here, such as VX steel rings. The main failure form of metal seals is deformation failure. According to on-site records, the VX steel ring used in the blowout preventer system would generally not lead to leakage in first time use, and the sealing effect is very good, but after a certain time, even if the surface is not deformed and damaged, there will be leakage due to the plastic deformation inside the steel ring, which reduces its preload and the uneven deformation and cannot guarantee the sealing effect. It is recommended that the used sealing ring should be replaced in time even if there is no deformation when it is used on site to avoid greater losses caused by repeated use.

(4) Failure of rubber core

Sealing the well is the main function of the blowout preventer system. To ensure the sealing effect, the reliability of the rubber core is very important. In addition to the wear and tear failures mentioned above, the causes of rubber core failure include fatigue damage, aging, deformation, corrosion, and tearing also need to be considered.

During the repeated opening and closing of the blowout preventer, the rubber core is subjected the repeated action by strong mechanical force, and cracks will gradually appear when the glue is dropped. Under the combined effect of erosion corrosion of downhole drilling fluid and the aging of the rubber core itself, it will speed up the formation of cracks. The cause of the aging of the rubber core is basically the same as the sealing ring, mainly due to improper storage. At present, the storage of rubber and rubber accessories such as rubber cores and sealing rings are not good enough. They are often stacked and pressed in large workshops with direct sunlight, and welding operations are often carried out near the rubber core storage, which could seriously accelerate the glue deformation and aging.

For manufacturers, it is recommended to strictly stipulate the effective storage period and storage standards of the rubber core and scrap the invalid rubber core in time. In addition, for the rubber core of the annular preventer, the long-term strong extrusion of the piston is likely to accelerate the aging of the rubber, it should be avoided by not using the annular preventer for a long time and the oil pressure should not be too large.

(5) Human factors

Human operation errors during installation and use are an important aspect of system failure. According to failure records, while installing the hydraulic connector to the wellhead, accidents caused leakage due to human error happened several times [5]. The accidents happened due to the low visibility of the seabed, the dropped sealing ring was not found, and the operator mistakenly regarded the hook of the connector as a metal sealing ring.

Fault tree analysis found out that it is common that improper operation done to the blowout preventer when opening, closing and locking. For example, if the annular BOP shuts down for a long time, the rubber core will be aged, and the oil circuit will be leaked.

From the above fault tree analysis, operator errors have the greatest impact on the blowout preventer failure, and the control system failures have the second greatest impact. Therefore, it is necessary to focus on preventing personnel errors from failing with the blowout preventer control system.

1. Operators should consciously receive safety training, strictly implement safety regulations, eliminate illegal operations, and complete their production tasks in good quality.

2. Strengthen the safety management, improve emergency management measures, and strengthen daily emergency exercises to improve staff's emergency response capabilities.

3. Regularly check and test the main control system to effectively find the problem and ensure that the problem is corrected in time.

6. Reliability allocation and prediction

6.1. Purpose of reliability allocation and prediction

In system design, as well as the actual production capacity, we must first put forward certain reliability indicators, such as reliability and loss rate within a specified time. The reliability of the system is closely related to the subsystems and components in the system. Reliability allocation is a method to reasonably allocate the reliability indexes required by the system to each unit of the system. The meaning of reliability allocation is to define the reliability index of the system, clarify the reliability requirements for each subsystem or component, provide reference standards for reliability testing and product acceptance, and allocate reliability according to the optimization method, which can help to achieve a more reasonable system design. Reliability prediction is a method to quantitatively estimate the reliability of future products at the initial stage of design. The exact reliability and lifetime of any product will only be calculated when the product was put in use and until broken, after getting enough history data. But more often, it is too late to take measures to improve the reliability when the product is already broken. Although it is difficult to accurate the early reliability prediction, but it helps to determine whether the design would be able to meet the customer's requirements or not.

Reliability allocation and prediction are both parts of reliability calculations, the result of reliability allocation is the target of reliability prediction, and the relative result of reliability prediction is the basis of reliability allocation and index adjustment. In the system design, these two steps might be repeated many times to achieve the optimization of the design. The workflow is shown in Figure 29: Workflow of probability allocation and prediction. [28]

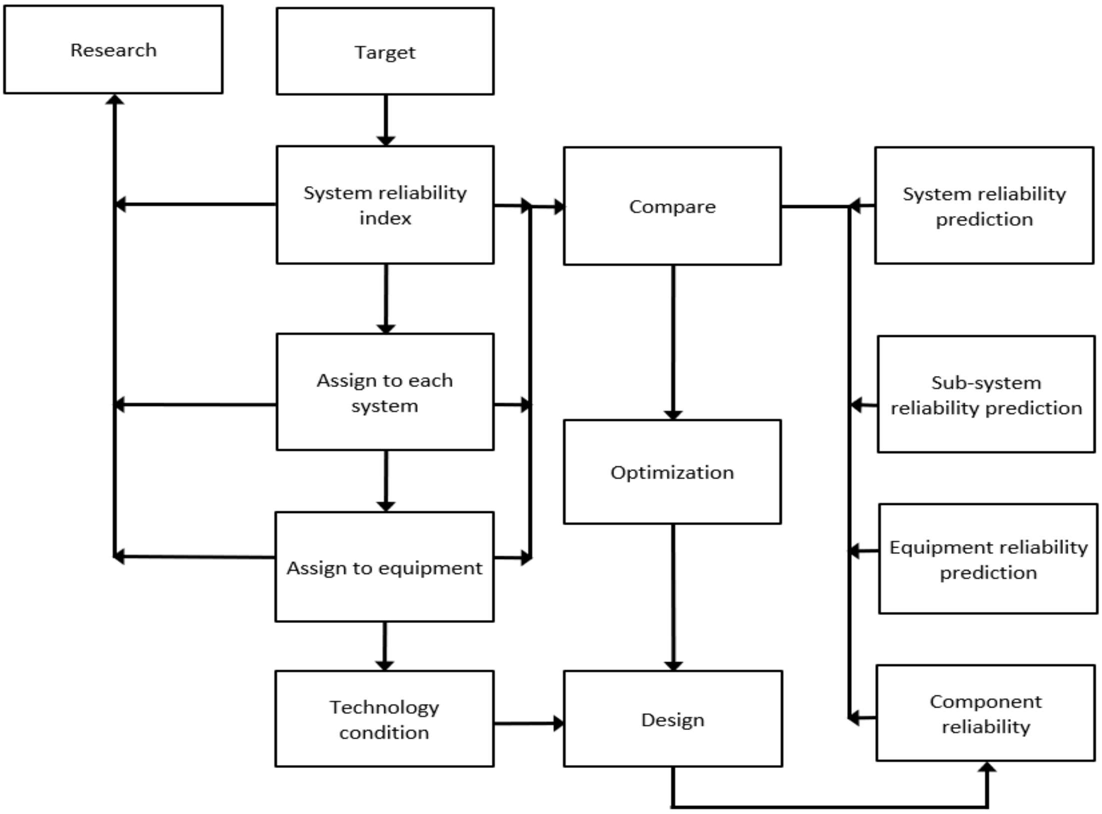

Figure 29: Workflow of probability allocation and prediction.

6.2. Reliability allocation of BOP system

If the BOP system is taken as a product, then the product has a strong "personality", which means that all factors must be considered when assigning reliability indicators. Some factors such as technical level and failure consequences cannot be quantitatively analysed, so a simple allocation method is not able to meet the requirements. AHP (Analytic Hierarchy Process) method is a mathematical method that often used in reliability allocation in recent years. It can comprehensively consider multiple factors and quantify factors through fuzzy mathematics theory and make the distribution results reasonable and accurate.

6.2.1. Reliability allocation implementing steps

(1) Building a hierarchical model

The establishment of a hierarchical model is the first step of the AHP. The hierarchy model divides the issue into different levels, including a higher level, a middle level and a lower level. The highest level is the target level, which represents the goal to be achieved by reliability allocation; the middle level is the criteria level, which corresponding to various factors that affect the reliability allocation, such as technical level, complexity of the system, working environment, etc.; the lowest level is the alternative level, which corresponding to each of the unit in the system.

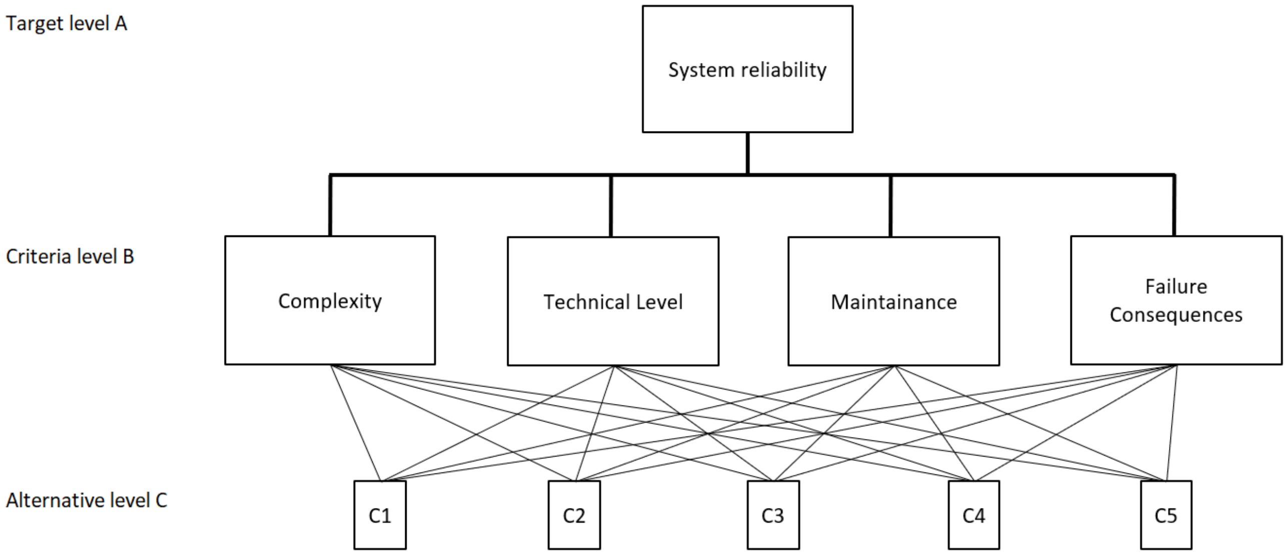

Figure 30: Hierarchical Model.

(2) Construct a judgment matrix

After the establishment of the hierarchical model, the relationship of the factors between the upper and lower levels is determined and the relative importance of each factor in each level needs to be judged. In the hierarchy analytic process, in order to quantify the judgments, these judgments are expressed numerically by introducing appropriate scales and written as a judgment matrix.

a_{ij} evaluation	**Meaning**
1	i and j are equally important
3	i is slightly important than j
5	i is obviously important than j
7	i is intensely important than j
9	i is extremely important than j
2,4,6,8	2, 4, 6, 8 means the value of adjacent judgment respectively
Reciprocal (1/ a_{ij})	1/ a_{ij} means the result of comparing i and j

Table 14: Judgement matrix.

(3) Calculate the eigenvector and take consistency test

There are two methods to calculate the eigenvector:

The summation method

a. Calculate the summation of each row in the matrix:

$$w_i = \sum_{j=1}^{n} a_{ij}$$

b. Renormalize it and get the eigenvector:

$$\omega_i = \sum_{j=1}^{n} a_{ij} / \sum_{k=1}^{n} \sum_{j=1}^{n} a_{kj}$$

Where i = 1, 2, …, n.

The square root method:

a. Calculate the mean of each row in the matrix:

$$\omega_i = \left(\prod_{j=1}^{n} a_{ij} \right)^{\frac{1}{n}}$$

b. Renormalize it and get the eigenvector:

$$\omega_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}} / \sum_{k=1}^{n} \left(\prod_{j=1}^{n} a_{kj}\right)^{\frac{1}{n}}$$

Where i = 1, 2, …, n.

Because expert opinions may diverge when constructing the judgment matrix, and the importance level assignment is not proportional. For consistency check of the judgment matrix, the following calculation result is only reasonable when the inconsistency of the matrix is within the acceptable range. Usually the consistency test of the judgment matrix is made by calculating the consistency ratio C.R.

$$C.R. = \frac{C.I.}{R.I.}$$

Where

$$C.I. = \frac{\lambda_{max} - n}{n - 1}$$

N is the order number of the judgment matrix.

R.I. is random index where can be checked in Table 15: Random index R.I. When C.R. < 0.1, it is considered that the consistency of the matrix is acceptable, and the feature vector w is the eigenvector, otherwise the judgment matrix needs to be reconstructed.

n	1	2	3	4	5	6	7	8	9	10
R.I.	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 15: Random index R.I.

(4) Calculate the eigenvector between levels

Calculate the eigenvectors for each two levels and get the relative importance of each alternative for the target.

The eigenvector of target level to criteria level is:

$$\omega^{(1)} = \left(\omega_1{}^{(1)}, \omega_2{}^{(1)}, \omega_3{}^{(1)}, \ldots, \omega_k{}^{(1)}\right)^T$$

The eigenvector of criteria level to alternative level is:

$$\omega^{(2)} = \left(\omega_{1l}{}^{(2)}, \omega_{2l}{}^{(2)}, \omega_{3l}{}^{(3)}, \ldots, \omega_{nl}{}^{(2)}\right)^T$$

Where l = 1, 2, …, k

Then the eigenvector of target level to alternative level is:

$$v^{(2)} = \left(v_1{}^{(2)}, v_2{}^{(2)}, v_3{}^{(2)}, \ldots, v_n{}^{(2)}\right)^T = \left[\omega_1{}^{(2)}\omega_2{}^{(2)}\omega_3{}^{(2)}\ldots\omega_n{}^{(2)}\right]\left[\omega_1{}^{(1)}\right]$$

This eigenvector calculated here need to be normalized. V_i represents the importance of alternative i to the system. The larger the v_i is, the more important the alternative means to the system.

(5) Reliability allocation

The distribution coefficient k_i is:

$$k_i = \frac{\frac{1}{v_i}}{\sum_{i=1}^{n} \frac{1}{v_i}}$$

If a series system has a failure probability λ_s and reliability R_s, then the alternative i have a allocated failure probability:

$$\lambda_i = \lambda_s k_i$$

and allocated reliability:

$$R_i = R_s^{k_i}$$

And each of the alternatives will have reliability:

$$R_1 = R_2^{(k_1/k_2)}$$

6.2.2. Reliability allocation of BOP with expected MTBF

In this part of thesis, for testing of the reliability allocation method, the proposed reliability goal of MTBF (mean time between failures) is set to one year (12 months). Since it is difficult to consider all possible situation and factors, there will be 5-10% of allocation allowance reserved to make sure the target will be reached, then the target MTBF is set to 400 days (instead of 365 days). Assume the failure distribution of the BOP system and each equipment conforms to the exponential distribution, the drilling time is calculated for 45 days in average, and the system reliability index Rs can be calculated as 0.894.

6.2.2.1. Reliability allocation model

Before the allocation process, the reliability allocation model should be established according to the specific conditions of the system, which include two steps:

(1) Building a reliability block diagram

System reliability includes basic reliability and mission reliability. Basic reliability refers to the time and probability of a product without failure under specified conditions. The basic reliability model is a full series model; any unit failure in the system requires repair and replacement. Therefore, the more devices in the system, the lower its basic reliability are. Basic reliability models are mostly used to measure the lifetime and maintenance costs of a system.

The mission reliability model can be used to describe the reliability for BOP system. The mission reliability model refers to the ability of a product to perform a specified function within a specified mission profile. It can be used to estimate the probability that the product will complete the specified task. Due to the special working conditions of the BOP system, every shutdown and maintenance will bring a certain loss. Therefore, if the equipment can work normally, it will usually not shut down for repairing or replacement. What is more important for the BOP system is the ability of the entire system to complete the task within the specified time and conditions. Therefore, when reliability is assigned, it is more appropriate to use the mission reliability model.

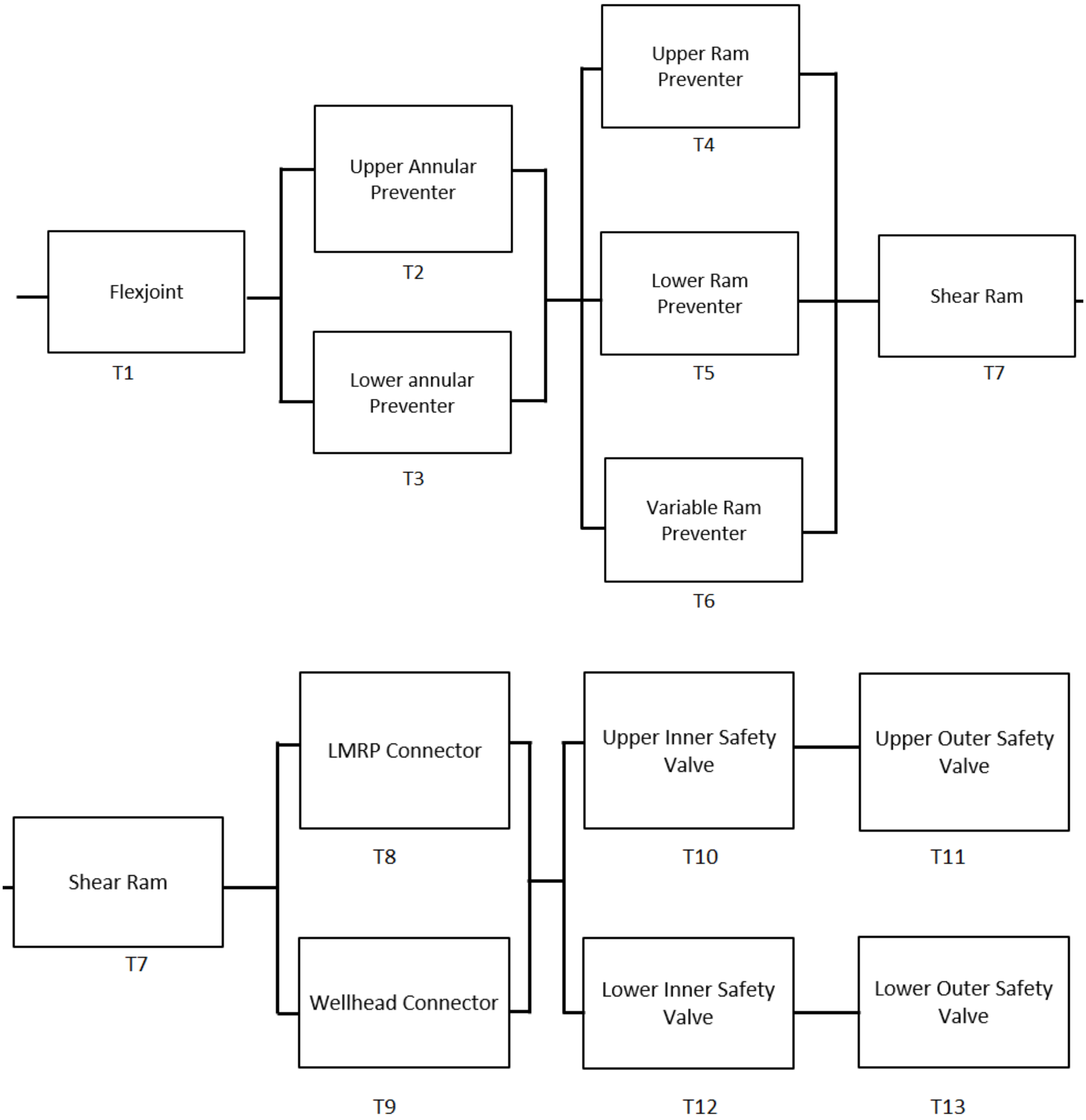

Figure 31: Reliability Distribution Model for BOP system.

(2) Determine the evaluation factor set

For a complex system, there are many evaluation factors that affect the system reliability allocation. The selection of evaluation factors affects the result of the reliability allocation in many ways. The product complexity, weight, size, technical level, failure consequences, risk, working time and working environment are all factors that usually need to be considered in reliability allocation. For each sub-system in the BOP system, the working environment and working time are the same, the weight and size have low effect on reliability, and the maintenance time and cost can be included in the evaluation of the failure consequences. In summary, the following factors are determined as evaluation factors for reliability allocation:

a. Complexity

The complexity of a device is usually measured by the number of components it contains. The more complex the product is, the more components it contains and the higher failure probability it gets. It will also be more difficult and more expensive to achieve higher system reliability. Therefore, for devices with high complexity, lower reliability indicators are usually to be assigned.

b. Technology level

Technology level is an important reliability evaluation factor. For the equipment with mature technology and advanced processing technology, the reliability level is relatively high, and a high reliability index should be assigned. For the BOP system, most of the equipment is mature technology and higher reliability indicators can be assigned here.

c. Failure probability

For higher failure probability, lower reliability indicator should be assigned. For lower failure probability, the reliability index can be assigned higher.

d. Failure detection difficulty

When failure happens on any equipment, if the time spending on failure determination is shorter, the loss caused by the failure and the possibility of bigger accidents will be less and lower. The difficulty of fault detection refers to the difficulty of equipment fault detection and diagnosis. It is closely related to the system reliability, so it is also listed as an evaluation factor for reliability allocation.

(3) Optimize the allocation model

The BOP system is a complex system includes several series and parallel connections, due to the complexity of the system, the reliability requirements of the components are also different. Therefore, the method of multiple allocations is adopted here, and by equivalent simplification and optimization of the system, the reliability is first allocated to the equipment, and then allocated to the sub-systems.

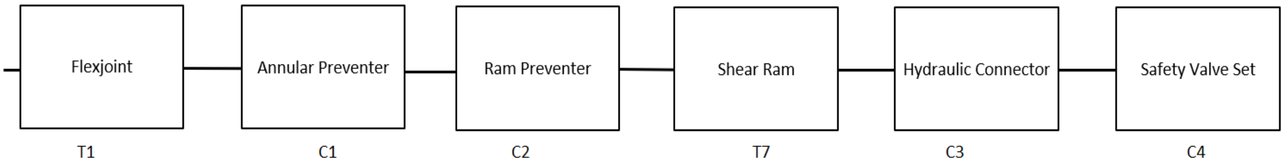

Figure 32: Simplified reliability distribution model of BOP system.

Therefore, the hierarchical model of system reliability allocation can be drawn as:

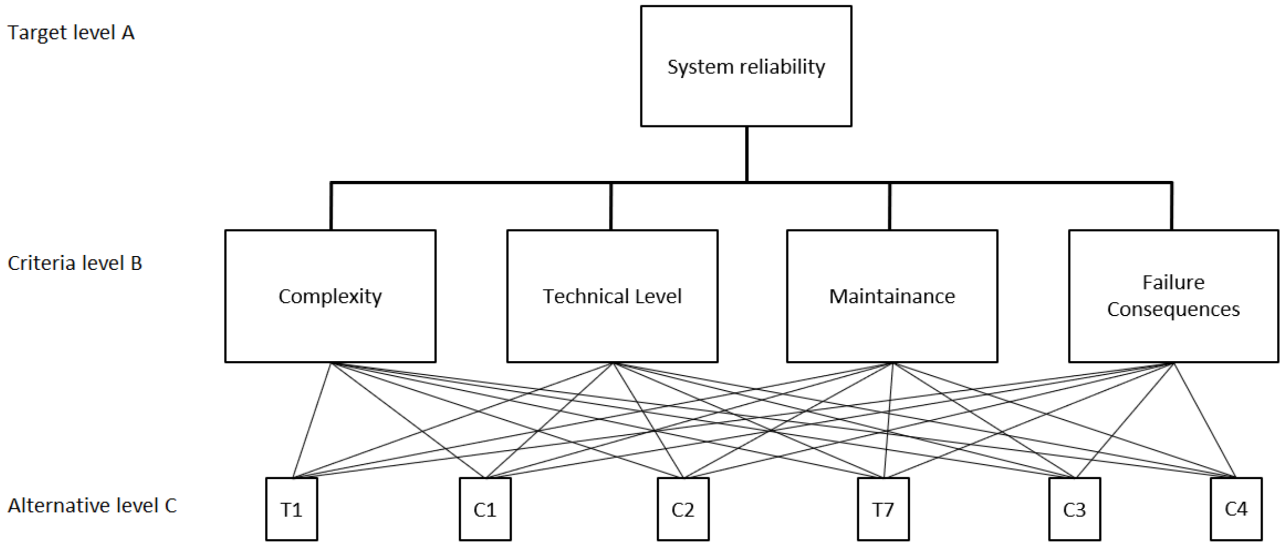

Figure 33: Analytical Hierarchy Model for BOP systems reliability distribution.

6.2.2.2. Construct a judgment matrix

Evaluate the degree of influence of the four evaluation factors on system reliability in previous chapter, make a comparison to construct the judgment matrix M of the criteria level B and the target level A.

$$M = \begin{bmatrix} 1 & 1/3 & 1/5 & 1/9 \\ 3 & 1 & 1/3 & 1/7 \\ 5 & 3 & 1 & 1/5 \\ 9 & 7 & 5 & 1 \end{bmatrix}$$

Then for each evaluation factor, compare each unit in the alternative level C, and construct the judgment matrix M_1 to M_4 of the alternative level C to the criteria level B.

$$M_1 = \begin{bmatrix} 1 & 3 & 7 & 7 & 5 & 5 \\ 1/3 & 1 & 5 & 5 & 3 & 3 \\ 1/7 & 1/5 & 1 & 1 & 1/3 & 1/3 \\ 1/7 & 1/5 & 1 & 1 & 1/3 & 1/3 \\ 1/5 & 1/3 & 3 & 3 & 1 & 1 \\ 1/5 & 1/3 & 3 & 3 & 1 & 1 \end{bmatrix} \quad M_2 = \begin{bmatrix} 1 & 5 & 5 & 7 & 1 & 3 \\ 1/5 & 1 & 1 & 3 & 1/5 & 1/3 \\ 1/5 & 1 & 1 & 3 & 1/5 & 1/3 \\ 1/7 & 1/3 & 1/3 & 1 & 1/7 & 1/5 \\ 1 & 5 & 5 & 7 & 1 & 3 \\ 1/3 & 3 & 3 & 5 & 1/3 & 1 \end{bmatrix}$$

$$M_3 = \begin{bmatrix} 1 & 7 & 3 & 3 & 5 & 2 \\ 1/7 & 1 & 1/5 & 1/5 & 1/3 & 1/6 \\ 1/3 & 5 & 1 & 1 & 3 & 1/2 \\ 1/3 & 5 & 1 & 1 & 3 & 1/2 \\ 1/5 & 3 & 1/3 & 1/3 & 1 & 1/4 \\ 1/2 & 6 & 2 & 2 & 4 & 1 \end{bmatrix} M_4 = \begin{bmatrix} 1 & 1/4 & 1/5 & 1/7 & 1/6 & 2 \\ 4 & 1 & 1/2 & 1/4 & 1/4 & 5 \\ 5 & 2 & 1 & 1/3 & 1/3 & 6 \\ 7 & 4 & 3 & 1 & 2 & 8 \\ 6 & 3 & 2 & 1/2 & 1 & 7 \\ 1/2 & 1/5 & 1/6 & 1/8 & 1/7 & 1 \end{bmatrix}$$

For matrix M. the maximum eigenvalue of the judgement λ_{max} =4.1707, C.R.= C.I. / R.I. = 0.6322 < 0.1. which meet the consistency. Using the same caluculation on matrix M_1 to M_4 and they all meet the consistency.

Then find out the eigenvector for each matrix by using summation method:

$$\omega = (0.0441, 0.1199, 0.2465, 0.5895)^T$$

$$\omega_1 = (0.4092, 0.2533, 0.0440, 0.0440, 0.1247, 0.1247)^T$$

$$\omega_2 = (0.3130, 0.0816, 0.0816, 0.0306, 0.3130, 0.1802)^T$$

$$\omega_3 = (0.3215, 0.0313, 0.1658, 0.1658, 0.0783, 0.2373)^T$$

$$\omega_4 = (0.0493, 0.1452, 0.1944, 0.3276, 0.0255, 0.028)^T$$

6.2.2.3. Calculate the allocation

According to the formulas in previous chapter:

$$v = [\omega_1 \omega_2 \omega_3 \omega_4]\,[\omega] = (0.1639, 0.1143, 0.1672, 0.2396, 0.2129, 0.1021)^T$$

Then the allocate coefficient k can be calculated:

K_{T1} = 0.1543, K_{C1}= 0.2221, K_{C2} = K_{C3} 0.1522, K_{C4} = K_{C5} = 0.2314, K_{C6} = 0.5373, K_{T7}= 0.1053, K_{C3}= 0.1185, K_{C4}= 0.2475

And the reliability for each alternative will be:

R_{T1}= 0.9829, R_{C1}= 0.9754, R_{C2}= 0.9831, R_{T7}= 0.9883, R_{C3}= 0.9868, R_{C4}= 0.9726

For alternative C_1, C_2, and C_3, the equipment structure is the same, so the same reliability index should be assigned, which can be directly calculated through the basic reliability calculation.

$$R_{T2} = R_{T3} = 1 - \sqrt{1 - R_{C1}} = 0.8432$$

$$R_{T6} = R_{T4}^{K_{T6}/K_{T4}} = R_{T4}^{2.322}$$

$$R_{C2} = 1 - (1 - R_{T4})^2 (1 - R_{T4})^{2.322} = 0.9831$$

$$R_{T4} = R_{T5} = 0.7969$$

$$R_{T6} = 0.5903$$

$$R_{T8} = R_{T9} = 1 - \sqrt{1 - R_{C3}} = 0.8851$$

$$R_{T10} = R_{T11} = R_{T12} = R_{T13} = \sqrt{1 - \sqrt{1 - R_{C4}}} = 0.9135$$

6.2.2.4. Allocation result

Combine the average MTBF for each equipment from the SINTEF report, and the calculation result from previous chapter, the reliability distribution of BOP system is shown in table below:

Equipment	**MTBF (day)**	**R**
Flexible Joint	2593.7	0.9829
Annular preventer	264.4	0.8432
Hydraulic connector	368.7	0.8851
Pipe ram	150.3	0.7969
Adjustable ram	155.7	0.5903
Shear ram	3791	0.9883
Safety valve	497.4	0.9135

Table 16: Reliability distribution of BOP system.

6.3. Reliability prediction of BOP system

Estimation of product reliability at an early stage used to be based on previous experience, especially the failure rate of components. Some common methods for system reliability prediction include mathematical model method, truth table method, and boundary value method.

For a complex mechanical system such as BOP system, the failure modes of its equipment are relatively complex. It is difficult to take all failure modes into account by establishing a unified reliability model. For example, when there is a failure in annular preventer, external leak lead to system failure, and if it is a function failure, it will not necessarily cause downtime.

The fault tree method can also be used for reliability prediction. As long as the top event is properly selected and can include all the failure modes of the system, the reliability of the system can be predicted by calculating the probability of the top event. Fault tree method will be used to complete the reliability prediction of the BOP system here.

6.3.1. Establish system fault tree

In this section, event "BOP Failure" is set as the top event in fault tree. Failure reason such as leakage, shut off failure, and accidents under abandoning are all included in the fault tree. In order to make the fault tree as comprehensive as possible but not too complicated, following failures are determined as a system failure:

- Leakage failure
- Equipment failure
- BOP shut off failure
- Failure of all parallel equipment
- Fail to open the well
- Well abandon
- Hydraulic connectors can be unlocked

According to the above principles, the system fault tree can be established as shown:

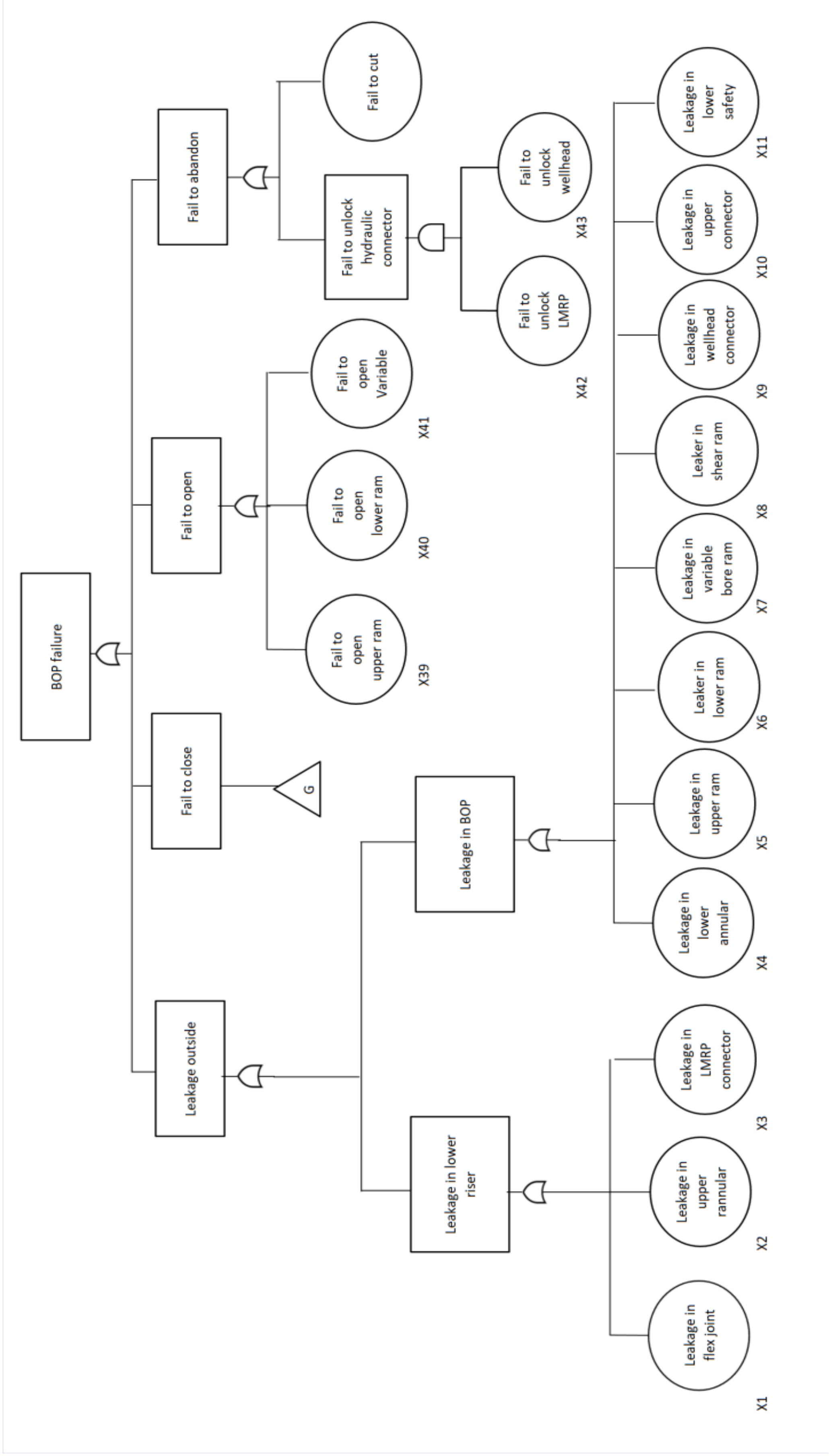

Figure 34: BOP system fault tree (a).

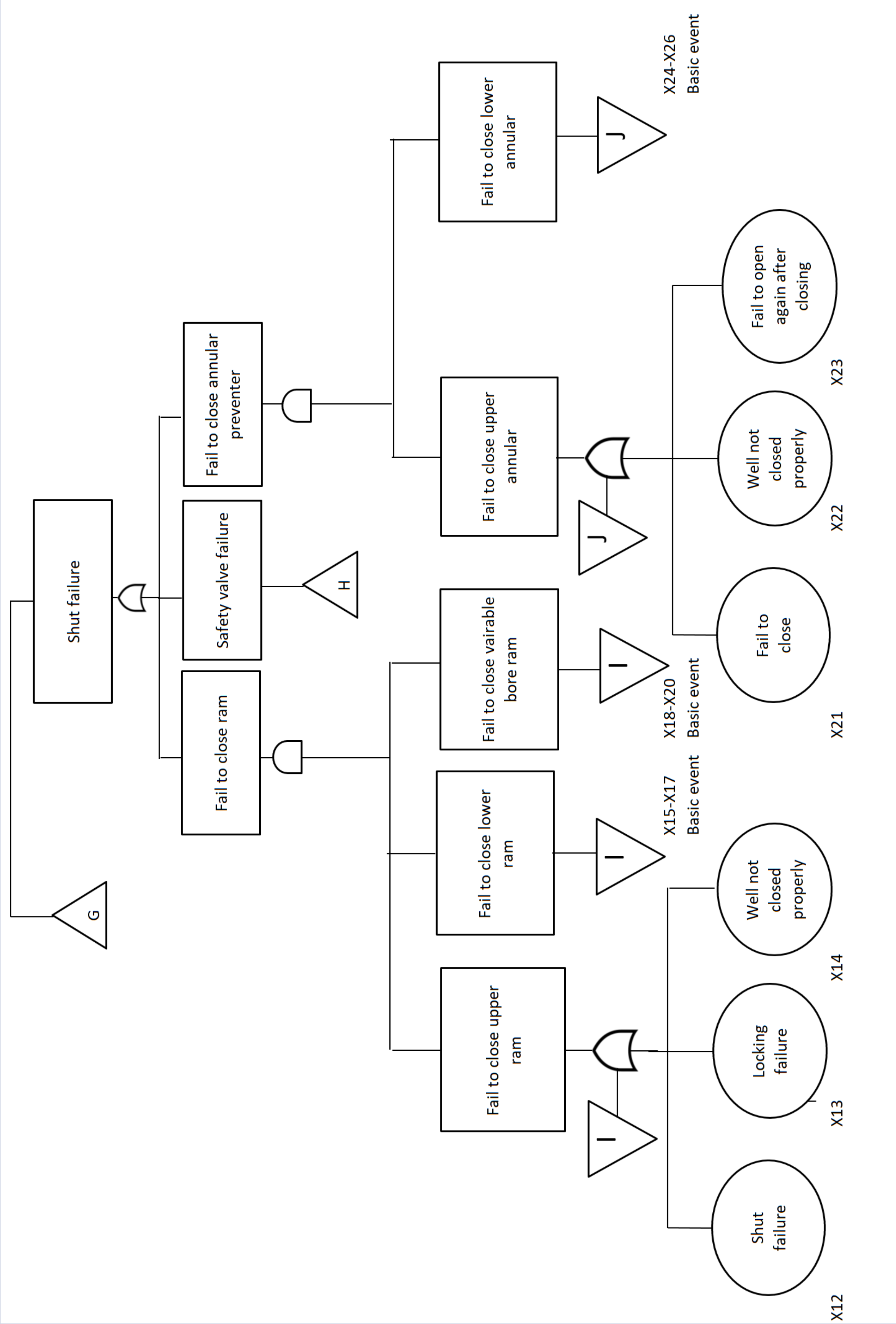

Figure 35: BOP system fault tree (b).

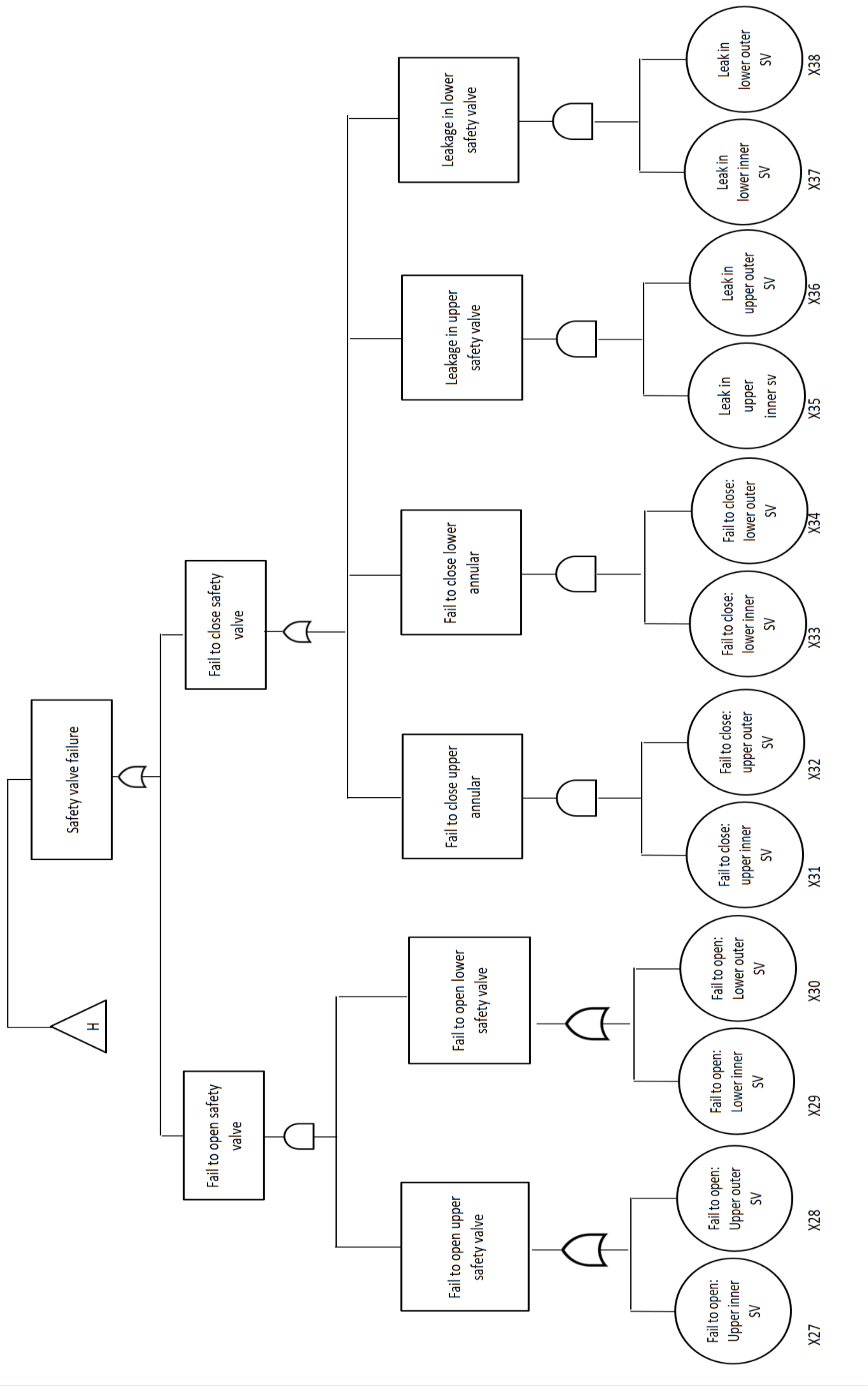

Figure 36: BOP system fault tree (c).

The probability of each failure mode can be calculated and summarized in Table 17:

Failure mode code	Probability	Failure mode code	Probability
X1	2.49	X23	8.052
X2	0.134	X24	0.134
X3	4.988	X25	8.052
X4	0.134	X26	8.052
X5	0.618	X27	0.3184
X6	0.618	X28	0.3184
X7	0.618	X29	0.3184
X8	0.618	X30	0.3184
X9	1.273	X31	0.3184
X10	4.988	X32	0.3184
X11	1.273	X33	0.3184
X12	0.618	X34	0.3184
X13	0.618	X35	1.9100
X14	2.47	X36	1.9100
X15	0.618	X37	1.910
X16	2.47	X38	1.910
X17	0.618	X39	1.853
X18	0.618	X40	1.853
X19	2.47	X41	1.853
X20	0.618	X42	7.485
X21	0.134	X43	7.485
X22	8.052	X44	0.618

Table 17: Probability for each failure mode.

6.3.2. Calculate the top event probability

The minimum cut sets of the fault tree are:

{P1}, {P2}, {P3}, {P4}, {P5}, {P6}, {P7}, {P8}, {P9}, {P10}, {P11}, { P12 P15 P18}, {P12 P15 P19}, {P12 P15 P20}, {P12 P16 P18}, {P12 P16 P19}, {P12 P16 P20}, {P12 P17 P18}, {P12 P17P19}, {P12 P17 P20}, {P13 P15 P18}, {P13 P15 P19}, {P13 P15 P20}, {P13 P16 P18}, {P13 P16 P19}, {P13 P16 P20}, {P13 P17 P18}, {P13 P17 P19}, {P13 P17 P20}, {P14 P15 P18},{{P14 P15 P19},{P14 P15 P20}, {P14 P16 P18}, {P14 P16 P19}, {P14 P16 P20}, {P14 P17 P18}, {P14 P17 P19}, {P14 P17 P20}, {P21 P23}, {P21 P24}, {P21 P26}, {P22 P23}, {P22 P24}, {P22 P26}, {P23 P25}, {P24 P25}, {P25 P26}, {P27 P29},{P27 P30}, {P28 P29}, {P28 P30}, {P31 P32}, {P33 P34}, {P35 P36}, {P37 P38}, {P39}, {P40 P41}, {P42}, {P43 P44}.

P_I is the probability of the basic event X_i in the fault tree show in Table 17. The failure rate of BOP system can be calculated:

$$\lambda_s = 2.396 * 10^{-3}(1/d)$$

Then the MTBF can be calculated:

$$MBTF_s = \frac{1}{\lambda_s} = 417.33(d)$$

Which meets the 400 days MBTF set value.

7. Conclusion

The research of this subject is combined with the design process of the product, with the goal of improving the reliability level of the product and meeting the needs of deep sea drilling operations.

This is done by fully drawing on the modern reliability engineering theory and related failure data and research results. Choosing a reasonable research method to complete the deep water reliability analysis and calculation of the lower blowout preventer unit has important theoretical significance and practical value.

The main work completed in this paper is as follows:

(1) Completed a literature research of BOP system and its reliability analysis method. Explain the importance of reliability analysis for BOP system in drilling operations related to risk and safety management.

(2) Completed a reliability analysis of the system, identifying the key components and the most serious failure modes of each of the equipment. Analysing the causes of failure from five aspects: Corrosion failure, wear failure, sealing failure, rubber core failure and human factors. Finally, some improvement suggestions for reducing the risk and hazard degree have been put forward for designing, manufacturing and use.

(3) Established a system reliability allocation model and used the analytic hierarchy process to calculate the reliability index of each component in the system according to the design goals proposed by the manufacturer.

(4) Completed system reliability prediction work. According to the predicted results, the average trouble-free working time of the BOP system of this scheme reached 417.33 days, which met the design requirements.

Further research work suggestions:

The reliability research of petroleum equipment, especially the reliability research of the blowout preventer system has been carried out in many methods in the recent years. Although this paper has done some work on the reliability research of the deep-water blowout preventer system, there is still much study and research can be done in the future. This is due to some details of the research object have not been finalized, some of the relevant data are insufficient, and limited research time

(1) Due to the limited research time and lack of detailed design information of the control system, the reliability of the control system is not discussed in this paper. The control system of the deep-water blowout preventer unit is a complex system of electromechanical and hydraulic integration, and its reliability is the key to the normal operation of the entire well control system. The historical failure data shows that, among the failures of the entire well control system, the proportion of failures caused by the control system is more than 50%. Therefore, it is very important to do special reliability research for the control system.

(2) Due to insufficient historical failure data, failure distribution parameters of each device cannot be calculated from existing data. Therefore, in the reliability prediction, all failure probabilities are calculated according to the exponential distribution, which reduces the accuracy of the prediction. In future research, if the failure data is supplemented, more accurate prediction and analysis can be made based on this paper.

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