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Risk Model applied to Non-operational Hydrocarbon Leaks on Offshore Installations

Causal modeling of hydrocarbon leaks
caused by technical degradation and design
error with the use of risk-influencing factors

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Abstract

This project proposes a risk model for identifying causal factors of hydrocarbon (HC) leaks on offshore installations and estimating the platform-specific frequency of HC leaks. The central concern is non-operational leaks caused by either technical degradation or design error.

The model development is based on the investigation of previous HC leaks incidents using incident investigation reports. The investigation covers 25 leaks which occurred in the UK, Norway, and the USA, and the relevant literature is also referred to for some types of leaks due to the small number of investigation reports. The techniques used for the modeling process are Bayesian Belief Network (BBN) and Event Tree Analysis (ETA).

The developed model provides the Risk-Influencing Factors (RIFs) for HC leaks caused by technical degradation and design error. The identified RIFs for leaks caused by technical degradation are divided into two types: the common RIFs applied to all types of technical degradation leaks and the specific RIFs applied to a certain type of technical degradation leaks. In case of leaks caused by design error, the RIFs are identified in the equipment and system levels. Since the identified RIFs are highly relevant to the specific condition of installations, it is verified that the platform-specific frequency needs to be applied to non-operational leaks, which has not been considered in conventional Quantitative Risk Assessment (QRA) studies.

With regard to the usage of this model, it is possible to assess the condition of an installation associated with the likelihood of HC leaks occurrence by evaluating the status of the identified RIFs on the installation in the same way as performed in previous work such as BORA-Release and the Risk OMT model. Then, generic leak frequencies are changed into installation-specific leak frequencies according to the assessed condition.

If further studies focus on the quantitative use of the developed model and the verification of the identified RIFs, the platform-specific frequency for all types of HC leaks can be estimated using this model combined with the Risk OMT model which covered operational leaks.

Preface

This master thesis has been written as a final part of the international MSc. program in Marine Technology at the Norwegian University of Science and Technology (NTNU), Department of Marine Technology. This work was carried out during the spring semester 2015.

I would like to thank my supervisor professor Jan Erik Vinnem at the Department of Marine Technology, NTNU, for the dedicated support and valuable feedback on my work with this thesis.

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Suyeon Kim

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Definitions

For purposes of this thesis, the following definitions shall apply.

Accident scenario: A specific sequence of events from an initiating event to an undesired consequences (harm) (IMO, 2002).

Consequence (end event): The outcome of an event expressed qualitatively or quantitatively, being a loss, injury, disadvantage, or gain. There may be a range of possible outcomes associated with an event (Rausand, 2011).

Design error: Inherent design error which can directly cause a hydrocarbon leak. It is distinguished from unfortunate design.

Generic leak frequency: Leak frequency estimated based on the statistical data of previous leak incidents.

Hazardous event: The first event in an accident scenario, if not controlled, will lead to undesired consequences (harm) to some assets (Rausand, 2011).

Hydrocarbon leak (release): gas or oil leak (including condensate) from the process flow, well flow, or flexible risers with a release rate greater than 0.1 kg/s (Sklet, 2005).

Initiating event: An event that triggers subsequent chains of events in an accident scenario (Rausand, 2011). In this thesis,

Leak scenario: An accident scenario with a hydrocarbon leak as the undesired consequences.

Non-operational leak: Hydrocarbon leak not caused by manual operations or interventions. The initiating events of this type of leak are technical issues and external events.

Operational leak: Hydrocarbon leak due to manual operations and interventions.

Platform (installation) specific leak frequency: Specific leak frequency modified from generic leak frequency based on the evaluation of the condition of a platform (installation)

Qualitative risk assessment (analysis): Risk assessment (analysis) in which probabilities and consequences are determined purely qualitatively (Rausand, 2011).

Quantitative risk assessment (analysis): Risk assessment (analysis) that provides numerical estimates for probabilities and/or consequences – sometimes along with associated uncertainties (Rausand, 2011).

Risk: The chance of something happening that will have an impact upon objectives. It is measured in terms of consequences and likelihood (AS/NZS 4360, 1995).

Risk analysis: Systematic use of available information to identify hazards and to estimate the risk to individuals, property, and the environment (IEC 60300-3-9, 1995).

Risk assessment: Overall process of risk analysis and risk evaluation (IEC 60300-3-9, 1995).

Risk influence diagram: A diagram to show the effect of the platform specific conditions with the use of risk-influencing factors on the occurrences (frequencies) of the initiating events or other events in accident scenarios (Sklet, 2005).

Risk-influencing factor: A set of relatively stable conditions influencing the risk (Hokstad, Jersin, & Sten, 2001).

Safety barrier: Measure that reduces the probability of realizing a hazard's potential for harm or reduces its consequences (Rausand, 2011).

Technical degradation: Degradation of system or equipment over time, including valve sealing degradation, flange gasket degradation, loss of bolt tensioning, fatigue, corrosion, and erosion.

Threat (hazard): A source of danger that may cause harm to an asset (Rausand, 2011).

Abbreviations

AEB	Accident Evolution and Barrier function
AISI	American Iron and Steel Institute
API	American Petroleum Institute
APS	Abandon Platform Shutdown
BBN	Bayesian Belief Network
BORA	Barrier and Operational Risk Analysis
BSEE	Bureau of Safety and Environmental Enforcement
CM	Corrective Maintenance
CPT	Conditional Probability Table
CRA	Corrosion Resistant Alloy
CUI	Corrosion Under Insulation
DAG	Directed Acyclic Graph
DFU	Definerte Fare- og Ulykkessituasjoner (defined hazards and accident conditions)
DNV	Det Norske Veritas
DOE	Department Of Energy (Unites States)
ED	Explosive Decompression
ESD	Emergency Shutdown
ETA	Event Tree Analysis
EUC	Equipment Under Control
FPSO	Floating Production Storage and Offloading
FTA	Fault Tree Analysis
HC	Hydrocarbon
HEP	Human Error Probability
HMI	Human Machine Interface
HP	High Pressure
HSE	Health and Safety Executive (UK)
KO	Knock-Out
LSH	Level Safety High
LTA	Less Than Adequate
MEI	Manual Electrical Isolation
MoC	Management of Change
MORT	Management Oversight and Risk Tree
MTO	Human, Technology, and Organization
NCS	Norwegian Continental Shelf
OMT	Organizational, Human, and Technical

OTS	Operational Condition Safety
P	Production
PCP	Production and Compression Platform
PM	Preventive Maintenance
PSA	Petroleum Safety Authority (Norway)
PSD	Process Shutdown
PSE	Pressure Safety Element
QRA	Quantitative Risk Assessment
RBI	Risk-Based Inspection
RGD	Rapid Gas Decompression
RIF	Risk-Influencing Factor
RNNP	Risikonivå i Norsk Petroleumsvirksomhet (Trends in risk level in the petroleum activity)
SCAT	Systematic Cause Analysis Technique
SCC	Stress Corrosion Cracking
STEP	Sequential Timed Events Plotting
UKCS	United Kingdom Continental Shelf
VGP	Visund Gas Project

1 Introduction

This chapter provides background information about the topic, objectives, scope, and limitations of this thesis. In addition, for the convenience of readers, the overall structure of the report is provided at the end.

1.1 Background

On July 6, 1988, a gas leak from a pump on an installation in the UK Continental Shelf (UKCS) led to severe explosions and fires, and 167 people lost their lives (Cullen, 1990). This is the story of a monumental accident in the UK, the Piper Alpha disaster. The accident became a trigger to change attitudes towards leak accidents in the UK; companies operating offshore installations in the UKCS now have to report leaks to the UK Health and Safety Executive (HSE), while the HSE collects this leak data for different sizes and types of equipment where the leak occurred, in a systematic manner (DNV, 2012). Furthermore, DNV realized a need to estimate leak frequency for process equipment on offshore installations, and developed a methodology based on data from the HSE in 2009 (Bolsover, Falck, & Pitblado, 2013). With this methodology, an operator can calculate the expected Hydrocarbon (HC) leak frequency of an installation, based on the number, type, and size of equipment on the installation (DNV, 2012).

Meanwhile, in Norway, the Petroleum Safety Authority (PSA) has collected data of HC leaks on offshore installations in the Norwegian Continental Shelf (NCS) since 2000, recognizing HC leaks as a critical indicator for safety (PSA, 2015). The methodology developed by DNV is used to estimate HC leak frequency for Quantitative Risk Assessment (QRA) studies in the Norwegian offshore industry. However, Vinnem (2014) pointed out differences between the UK and the Norwegian sectors: 1) The installations in the southern part of the UKCS are far different from the installations in the NCS, in terms of the size and complexity of installations. 2) The distributions of initiating events of leaks in the UK and the Norwegian sectors are also dissimilar. These differences could make it unsuitable to apply the methodology based on data in the UKCS to the Norwegian sector. Moreover, “generic” frequencies calculated by conventional QRA models such as the DNV methodology, have the inherent limitation of being unable to account for installation-specific conditions (Arnhus, 2014).

With this background, a new method was developed in Norway for analyzing the platform-specific HC release frequency, called Barrier and Operational Risk Analysis of HC release (BORA-Release) (Aven, Sklet, & Vinnem, 2006; Sklet et al., 2006). BORA-Release made it possible to evaluate the risk of HC release and the effect of relevant barriers of a certain offshore platform, by considering platform-specific conditions of Risk-Influencing Factors (RIFs) (Aven et al., 2006). Also, the Risk modeling – integration of Organizational, Human, and Technical factors (Risk OMT) program represented a further development of the work in BORA-Release, with more emphasis on RIF modeling and the performance of operational barriers (Vinnem et al., 2012). Compared to BORA-Release, the Risk OMT program proposed a determined model, called the Risk OMT model, including generic leak scenarios, fault trees, and RIF models for HC leaks associated with human interventions. Therefore, the frequency of HC leaks caused by human interventions can be estimated only with the evaluation of conditions of the RIFs identified in the Risk OMT model.

However, there are still difficulties in calculating the platform-specific frequency of non-operational leaks (which are not caused by human interventions) because there is no further work of BORA-Release such as the Risk OMT program to present a determined model, in case of non-operational leaks. Therefore, this study will develop a model to estimate the platform-specific frequency of non-operational leaks.

1.2 Objectives

The objective of this thesis is to deliver a risk model applied to non-operational HC leaks on offshore installation. This model consists of event trees illustrating the leak scenarios and RIF models for the events causing the leaks (initiating events), thus they can be used to assess the condition of an installation with regard to an HC leak occurrence. To identify the leak scenarios and the RIFs, previous leak incidents are also investigated.

1.3 Scope and limitations

The model to be developed in this thesis deals with non-operational HC leaks because they were not considered in the Risk OMT model. Although there are four types of non-operational leaks such as leaks caused by technical degradation, process disturbance, design errors, and external events, two types associated with technical degradation and design errors are modeled only because the number of occurrence of the other two types is negligible.

Although the model to be developed in this thesis can be used quantitatively in the same way in BORA-Release and the Risk OMT model, it is not applied to this project.

Finally, previous leak investigation reports used to identify the leak scenarios and the RIFs are not fully reliable because, according to the PSA (2011), accident investigation reports do not provide every bit of information either intentionally or unintentionally. Moreover, the number of investigated previous leaks for some types of leaks is not enough though a review of relevant literature compensates for this. Due to these limitations, there may be missing RIFs or events in the model.

1.4 Structure

The structure of this thesis is as follows:

- Chapter 2 explains HC leaks as a critical hazardous event in the offshore oil and gas industry. HC leaks, being the main topic, are covered with regard to their occurrence, consequence, and previous studies. The concepts of leak scenarios and initiating events are also explained because they are used for this study.
- Chapter 3 introduces different accident investigation methods, and shows the selection of the method to be used in this thesis. Accident investigation is essential to figure out factors influencing the occurrence of HC leaks.
- Chapter 4 covers risk analysis, specifically RIFs and three methods; Bayesian Belief Network (BBN), Event Tree Analysis (ETA), and Fault Tree Analysis (FTA). BBN and RIFs are explained as the main method and concept of the model of this project. ETA and FTA used in BORA-Release and the Risk OMT model are also covered briefly.
- Chapter 5 introduces BORA-Release and the Risk OMT model, which are the previous risk models for HC leaks with the same approach as in this thesis.
- Chapter 6 presents the investigation of 25 leak incidents. The leaks caused by technical degradation or design errors are the main concern.

- Chapter 7 describes the process of modeling HC leaks based on the investigated leaks. The leaks are divided into two categories according to their initiating events (technical degradation or design errors), and are modeled separately.
- Chapter 8 evaluates the model developed in this study. The validity and quantitative use of the model and alternative approaches are discussed.
- Chapter 9 concludes this thesis, and suggests further work.

2 Hydrocarbon leaks

Hazardous events for personnel on offshore installations are HC leaks, well control incidents, vessel on collision course, structural failures, etc. (PSA, 2014b). Among these, HC leaks are one of the major events. This chapter will briefly describe the risk of and previous studies on HC leaks.

2.1 Risk of HC leaks

HC leaks indicate the leaks of multiple types of hydrocarbons including gas, two-phase, and unstabilized and stabilized liquid petroleum, but refined products are not covered in the Norwegian classification. The corresponding term in the UK is HC release, even refined hydrocarbon products, such as lube oil, hydraulic oil, weal oil, and diesel, are included in the UK (Vinnem, 2014).

HC leaks are considered one of the main risks of major accidents in the offshore industry, in terms of its occurrence and consequence.

The number of occurrences of HC leaks can be found in the trend in risk level in the petroleum activity (RNNP process) outlined by the PSA, in order to measure and improve health, safety and environmental conditions in the offshore industry. Here, HC leaks are among the defined hazards and accident conditions (DFUs), which represent critical indicators for safety and the working environment (PSA, 2015). Even among DFUs, HC leaks occur rather frequently as shown in Figure 2.1 (blue).

The Piper Alpha disaster is one example that shows how severe the consequences of HC leaks can be. A monumental accident in the UK in 1988, the Piper Alpha disaster was caused by a gas leak and ended in large fires and 165 fatalities (Cullen, 1990).

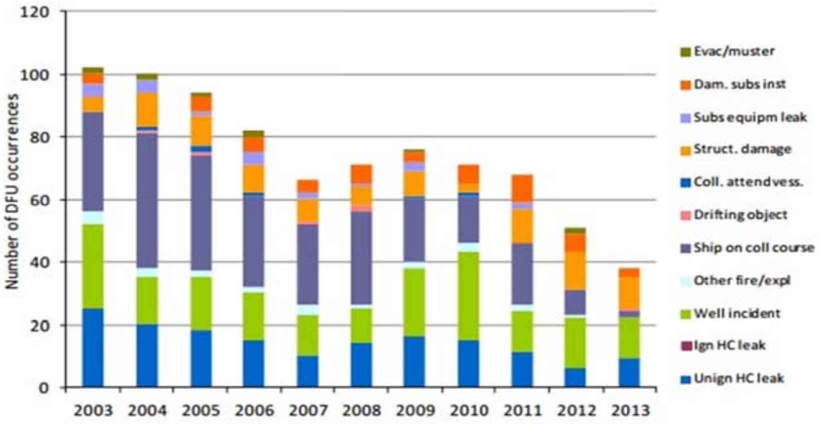


Figure 2.1 Number of DFU occurrences (PSA, 2014b)

2.2 Analysis of HC leaks in the Norwegian offshore industry

It has been recognized that the risk of HC leaks is crucial, and the causes and barriers have been actively studied to prevent HC leaks in the Norwegian offshore industry.

One example is the RNNP process already mentioned in Chapter 2.1. HC leaks are among the DFUs; thus, the data such as the number of occurrences, causes, and leak rates are reported and collected annually. The leaks are not only classified according to their rates but also compared with leaks in the UK and analyzed based on their causes (PSA, 2014b).

In addition, the Norwegian Oil and Gas Association conducted a reduction project from 2003 to 2008, the aim being to reduce the number of HC leaks on offshore production installations on the NCS. It resulted in a great reduction of HC leak occurrence from more than 40 leaks (leak rate greater than 0.1 kg/s) per year in 2000 to 10 leaks in 2007. Later, the Norwegian Oil and Gas Association started a new project in 2011 (Vinnem & Røed, 2014).

There were also BORA-Release as part of the BORA-project, which presented a method for risk analysis of the platform-specific HC leak frequency, and its further development, the Risk OMT model. BORA-Release and the Risk OMT model are highly relevant to the topic of this thesis and will be discussed at length in Chapter 5.

2.3 Accident scenario

A sequence of events including an HC leak—in other words, an accident scenario of an HC leak—deserves consideration before analyzing the risk of HC leaks. This helps to see the causes and results of HC leaks at a single glance, and to establish proactive and reactive safety barriers.

2.3.1 Bow-tie diagram

An accident scenario with an HC leak as a hazardous event, initiated from corrosion and ending up with pollution, is presented in a bow-tie diagram, Figure 2.2. A bow-tie diagram "illustrates that various hazards/threats may lead to a hazardous event, and that the hazardous event may in turn lead to many different consequences" (Rausand, 2011, pp.5). With HC leaks as a hazardous event, hydrocarbons are the hazard or threat. Several events such as corrosion and opening pressurized equipment may initiate a HC leak, and consequences may be fatalities or pollution to sea. The focus of this thesis is placed on the left side of the bow-tie, which means from hazards/threats to HC leaks.

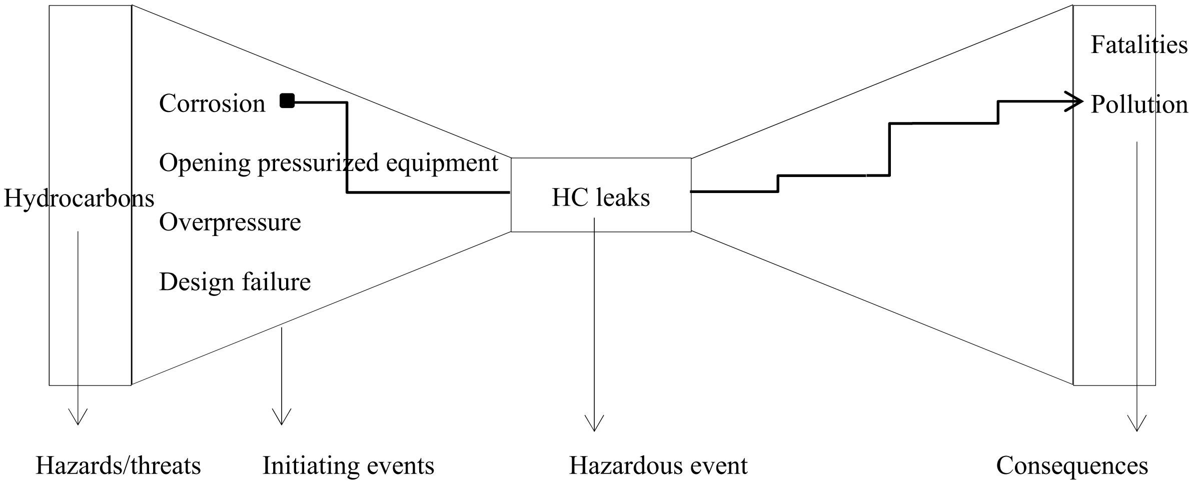


Figure 2.2 Accident scenario involved HC leaks in a bow-tie diagram

2.3.2 Initiating events

Although "an initiating event is an analytical concept, which is entirely up to the analyst to choose" (Rausand, 2011, pp.31), the author adapts the initiating events for HC leaks identified in BORA-Release. This is because the study in this thesis is on the basis of BORA-Release and its further development, the Risk OMT model, in many aspects. The initiating events will be used to classify HC leaks scenarios throughout the thesis. An overview of the initiating events in BORA is presented in Table 2.1.

Table 2.1 Overview of the initiating events in BORA (Vinnem, Seljelid, Haugen, & Husebø, 2007)

Initiating event type	Initiating events (subcategories)
A. Technical degradation of system	1. Degradation of valve sealing 2. Degradation of flange gasket 3. Loss of bolt tensioning 4. Fatigue 5. Internal corrosion 6. External corrosion 7. Erosion 8. Other causes
B. Human intervention – introduction latent error	1. Incorrect blinding/isolation 2. Incorrect fitting of flanges or bolts during maintenance 3. Valve(s) in incorrect position after maintenance 4. Erroneous choice or installations of sealing device 5. Maloperation of valve(s) during manual operation 6. Maloperation of temporary hoses
C. Human intervention – causing immediate release	1. Break-down of isolation system during maintenance 2. Maloperation of valve(s) during manual operation 3. Work on wrong equipment, not known to be pressurized
D. Process disturbance	1. Overpressure 2. Overflow/overfilling
E. Inherent design errors	1. Design related failures
F. External events	1. Impact from falling object 2. Impact from bumping/collision

3 Accident investigation

Identification and selection of RIFs on each type of initiating event of HC leaks is required prior to risk modeling applied to HC leaks, which is the objective of the thesis, and it is possible by investigating previous HC leak accidents/incidents. This chapter outlines different accident investigation methods for different purposes and explains events and causal factors charting, the methodology that will be used in the thesis.

3.1 Purpose and methods of accident investigation

An accident investigation may have different purposes (Sklet, 2002):

- Identify and describe the true course of events (what, where, when)
- Identify the direct and root causes / contributing factors of the accident (why)
- Identify risk reducing measures to prevent future, comparable accidents (learning)
- Investigate and evaluate the basis for potential criminal prosecution (blame)
- Evaluate the question of guilt in order to assess the liability for compensation (pay)

The thesis focuses on the first two purposes, identification of the course of events and the causes. Identifying the causes needs more attention in the light of the nature of accidents that result from multiple, interrelated causal factors rather than a single cause (DOE, 1999). In addition, this study sets a goal of simple and quick investigation for a single incident, in order to deal with as many incidents as possible to determine common causes for each initiating type of HC leaks.

To find out a method to meet these requirements, a comparison of several accident investigation methods is presented in Table 3.1. Refer to Sklet (2004) for more detailed explanation about each method. It shows whether an event sequence of an accident can be presented and causal analysis is possible with the method, in the second and third columns, respectively. The last column, levels of analysis, means the level of scope of the different analysis methods (from the work and technological system to the government level). The level of representation with the numbers 1-6 is also adapted from Sklet (2004), and can be found in Table 3.2. If the scope of a method is limited to 1 or 2 levels, it is difficult to discover an underlying cause of an accident, which maybe a management fault. On the other hand, a method of wide scope is used for an in-depth analysis, but it can be complex and time-consuming.

Table 3.1 Characteristics of accident investigation methods (Sklet, 2004)

Method	Accident sequence	Causal analysis	Levels of analysis
Event and causal factors charting	Yes	Yes	1-4
Barrier analysis	No	No	1-2
Change analysis	No	Yes	1-4
Root cause analysis	No	Yes	1-4
Fault tree analysis	No	Yes	1-2
Influence diagram	No	Yes	1-6
Event tree analysis	No	No	1-3
MORT	No	Yes	2-4
SCAT	No	Yes	1-4
STEP	Yes	No	1-6
MTO-analysis	Yes	Yes	1-4
AEB-method	No	Yes	1-3
TRIPOD	Yes	Yes	1-4
Acci-Map	No	Yes	1-6

Table 3.2 Level of scope of analysis methods (Sklet, 2004)

Number	Level of scope
1	The work and technological system
2	The staff level
3	The management level
4	The company level
5	The regulators and associations level
6	The government level

Events and causal factors charting is selected as a result of the comparison. The method is available for the presentation of an events sequence and causal analysis. Furthermore, the scope is broad enough to cover the management and the company levels, and the method is easy to use. A detailed description of the method is provided in Chapter 3.2.

3.2 Events and causal factors charting

“Events and causal factors charting is a graphical display of the accident's chronology and is used primarily for compiling and organizing evidence to portray the sequence of the accident's events” (DOE, 1999). Furthermore, it is useful in identifying multiple causes since it represents the conditions along with the event sequence. DOE (1999) points out the benefits of the method:

- Illustrating and validating the sequence of events leading to the accident and the conditions affecting these events
- Showing the relationship of immediately relevant events and conditions to those that are associated but less apparent — portraying the relationships of organizations and individuals involved in the accident
- Directing the progression of additional data collection and analysis by identifying information gaps
- Linking facts and causal factors to organizational issues and management systems
- Validating the results of other analytic techniques
- Providing a structured method for collecting, organizing, and integrating collected evidence
- Conveying the possibility of multiple causes
- Providing an ongoing method of organizing and presenting data to facilitate communication among the investigators
- Clearly presenting information regarding the accident that can be used to guide report writing
- Providing an effective visual aid that summarizes key information regarding the accident and its causes in the investigation report.

The primary chain of events that led to an accident mainly comprises the events and causal factors chart. The conditions for the events and secondary events are then added to the chart. Illustration of the basic format is in Figure 3.1 and guidelines for constructing the chart are in Table 3.3.

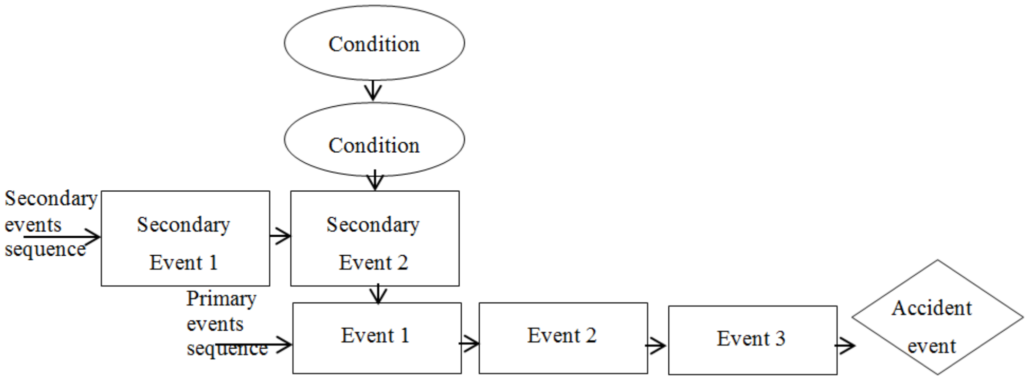


Figure 3.1 Illustration of the basic format of events and causal factors charting (DOE, 1999)

Table 3.3 Guidelines and symbols for preparing an events and causal factors chart (DOE, 1999)

Symbols	□ - Events ◇ - Accidents ⬭ - Conditions ⬚ - Presumptive events ◌ - Presumptive conditions or assumptions → - Connect events and conditions ▷ - Transfer one line to another LTA – Less Than Adequate (judgment)
Events	Are active (e.g., "crane strikes building") Should be stated using one noun and one active verb Should be quantified as much as possible and where applicable (e.g., “the worker fell 26feet,” rather than, “the worker fell off the platform”) Should indicate the date and time, when they are known Should be derived from the event or events and conditions immediately preceding it
Conditions	Are passive (e.g., "fog in the area") Describe states or circumstances rather than occurrences or events As practical, should be quantified Should indicate date and time if practical/applicable Are associated with the corresponding event
Primary event sequence	Encompasses the main events of the accident and those that form the main events line of the chart
Secondary event sequence	Encompasses the events that are secondary or contributing events and those that form the secondary line of the chart

4 Risk analysis

In contrast to accident investigation, risk analysis is a proactive approach for dealing exclusively with potential accidents. In other words, accident investigation is a reactive method to determine the causes and circumstances of accidents that have already happened, while risk analysis estimates the risk of the identified hazard based on the determined causes and circumstances (Rausand, 2011). In this thesis, risk analysis finds typical accident scenarios and the frequency of HC leaks based on the investigation result. This chapter focuses on the tasks of risk analysis, and then provides a detailed description of RIFs, playing a major role in risk analysis of this thesis. In addition, three risk analysis methods used for BORA-Release and the Risk OMT model—BBN, ETA, and FTA—are covered.

4.1 Three main steps

What tasks are involved in risk analysis? Kaplan and Garrick (1981) assert that a risk analysis consists of an answer to the following three questions:

i. What can happen? (i.e., what can go wrong?)
ii. How likely is it that it will happen?
iii. If it does happen, what are the consequences?

Providing answers to the three questions is the tasks of risk analysis. Rausand (2011) names these as the three main steps of risk analysis and explains them using risk terminology:

Hazard identification is carried out to answer the first question. A hazard is defined as “ a source of danger that may cause harm to an asset” (Rausand, 2011, pp.66). For example, hazards or threat can include toxic substances, high speed/pressure, explosive materials, radiation, etc. An analyst needs to identify the threat, considering the characteristics of the system and the asset.

The second question indicates the frequency of a hazardous event. A threat itself does not lead to negative consequences, but there is possibility that threats can progress to several hazardous events such as release of toxic substances, high-speed collision, and explosion. In this step, how possibly (how frequently) a hazardous event occurs is estimated. This is called frequency analysis.

However, a hazardous event does not always have a same consequence. For instance, the release of a toxic substance can kill many people, but, if the release is controlled, it can end in minor damage to a property or even no harmful result. Thus, the various consequences of a hazardous event are analyzed in the last step of risk analysis.

The three main steps are illustrated in Figure 4.1. If a hazardous event is identified or selected for analysis, the threats that may develop into the hazardous event are identified in the first step, and the frequencies are estimated in the second step. At the end, the different consequences that the hazardous event can cause are analyzed.

Figure 4.1 can be compared with Figure 2.2: In case of an HC leak as the identified hazardous event, the threat is mainly hydrocarbons, and the consequences vary from no harm to fatalities. The purpose of this thesis is the estimation of HC leak frequency, which is the answer to the second question. For frequency estimation, risks that could cause HC leaks need to be identified and factors that influence on these risks (RIFs) are also a matter of concern. Therefore, the focus of this project is placed on the left side of Figure 2.2 and Figure 4.1.

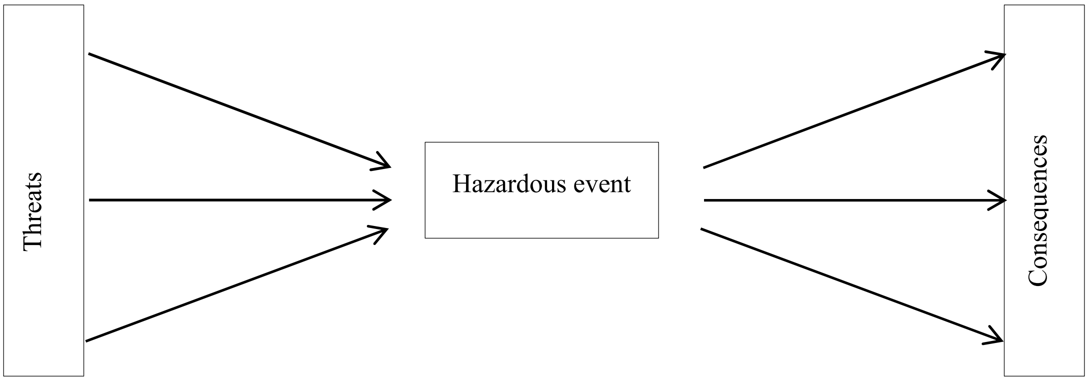


Figure 4.1 Illustration of the three main steps of risk analysis

4.2 Risk-influencing factor

RIF plays an important role in the modeling of this project and will be used in BBN. This section will describe its concept and discuss on how to select the relevant RIFs for certain types of accidents.

4.2.1 Generic RIFs

A RIF is defined by Hokstad et al. (2001) as “a set of relatively stable conditions influencing the risk”, in other words, a RIF is the average level of some conditions, having an impact on the frequency or consequence of an accident (Hokstad et al., 2001). Similarly, Rahimi and Rausand (2013) claims that RIFs are covariates and that changes in them will increase or reduce a constant (or assumed constant) failure rate of an item in the oil and gas industry.

Then, what kinds of things can be RIFs? RIFs vary in different industries and accidents, but Aven et al. (2006) identify generic RIFs for HC leaks on offshore production platforms. The generic RIFs cover human, operational, organizational, and technical RIFs on the occurrences of the initiating events (see Chapter 2.3.2) and the barrier (which prevents HC leaks from an initiating event) performance. The list of generic RIFs is presented in Table 4.1. Then, specific RIFs for each initiating event can be selected from the generic RIFs. For example, Sklet et al. (2006) select process complexity, maintainability/accessibility, task complexity, time pressure, and competence of mechanics as the RIFs for the initiating event B2, incorrect fitting of flanges during maintenance (see Table 2.1).

The limitation of the generic RIFs identified by Aven et al. (2006) is that they focused mainly on human, organizational, and operational RIFs rather than technical RIFs since they mostly analyzed the HC leaks due to human intervention. The RIFs on the initiating events (either latent errors or immediate releases) and the barrier performance are both covered for the HC leaks due to human intervention, however, for technical leaks such as leaks due to internal corrosion they gave more weight to inspection, condition monitoring , and leak detection, which are the events occurring after technical failure.

The generic RIFs with a focus on technical characteristics can be found in the research of Brissaud, Charpentier, Fouladirad, Barros, and Bérenguer (2010) and are presented in Table 4.2. The generic RIFs shown both in Table 4.1 and Table 4.2 will be considered and new RIFs can be added in the process of modeling.

Table 4.1 List of generic RIFs (Aven et al., 2006)

RIF group	RIF
Personal characteristics	Competence Working load / stress Fatigue Work environment
Task characteristics	Methodology Task supervision Task complexity Time pressure Tools Spares
Characteristics of the technical system	Equipment design Material properties Process complexity HMI (Human Machine Interface) Maintainability / accessibility System feedback Technical condition
Administrative control	Procedures Work permit Disposable work descriptions
Organizational factors / operational philosophy	Programs Work practice Supervision Communication Acceptance criteria Simultaneous activities Management of changes

Table 4.2 RIFs according to the system life phase (Brissaud et al., 2010)

Category		RIFs
Design		System type Working principle Dimensions (size, length, volume, weight) Materials Component quality (quality requirements, controls) Special characteristics (supply)
Manufacture		Manufacturer Manufacture process (procedures, controls)
Installation		Locations (access facilities) Assembly / Activations (procedures, controls)
Use	EUC	Equipment Under Control (EUC) type Special characteristics
	Solicitation	Type of load (cycling, random) Frequency of use Loading charge / Activation threshold Electrical load (voltage, intensity)
	Environment	Mechanical constraints (vibration, friction, shocks) Temperature Corrosion / Humidity Pollution (dust, impurities) Other stresses (electromagnetism, climate)
	Requirements	Performance requirements Failure mode (recorded failures)
Maintenance		Frequency of Preventive Maintenance (PM) Quality of PM Quality of Corrective Maintenance (CM)

4.2.2 RIF selection

Based on generic RIFs, specific RIFs for a certain type of accidents are selected. There are multiple criteria and methods for selecting RIFs, and the method proposed by Øien (2001) seems appropriate. As the first step to establish risk indicators, the selection of categories of accidental events is suggested, because the relevant RIFs vary with the accident type. In this thesis, initiating events (Table 2.1) will be used to categorize the leaks, and the RIFs contributing to each initiating event are identified through investigation of previous leak incidents.

4.3 Bayesian belief network

A BBN is “a graphical model that illustrates the causal relationships between key factors (causes) and one or more final outcomes in a system” (Rausand, 2011, pp.294). A BBN is mainly used to model the network of influences on a hazardous event or on an accident in a risk analysis (Rausand, 2011), thus it is suitable for modeling the network of RIFs on HC leaks. Not only are BORA-Release and the Risk OMT model based on a BBN, but the model to be developed in this thesis will also apply it. This chapter mainly explains the quantitative analysis using it, because it is indispensable for understanding the concept of BORA-Release and the Risk OMT model to be presented in Chapter 5.

4.3.1 Method description

As mentioned, a BBN is used for representing causal relationships. To explain the advantage of a BBN in representing the causal relationships, let us take an example from Kjaerulff and Madsen (2008).

smoking → bronchitis

which denotes the rule

R: if smoking then bronchitis.

It is correct that smoking is a cause of bronchitis, but the rule seems inappropriate for the causal relation between smoking and bronchitis because only a certain proportion of people who smoke suffer from bronchitis. This is the causal relation with uncertainty, and the vast majority of cause-effect mechanisms are uncertain. Researchers used a probabilistic method, BBN to explain this (Kjaerulff & Madsen, 2008). A BBN can express the uncertainty with a probability (the probability that A causes B in Figure 4.2, for example).

A BBN diagram like Figure 4.2 is called a Directed Acyclic Graph (DAG) which is made up of nodes describing states or condition and directed links indicating direct influences.

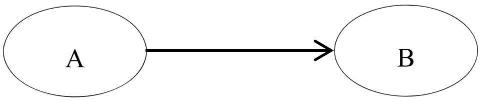


Figure 4.2 A simple BBN

4.3.2 Quantitative analysis

An example from Charniak (1991) is adopted to discuss the quantitative use of a BBN, and illustrated in Figure 4.3. It represents the situation that he can hear his dog barking when he comes home. This is because the dog is in the back yard, and his family put the dog out when leaving home. However, the dog is also out when she has bowel troubles. There is one more node indicating that the outdoor light is on, which his family also do when leaving home.

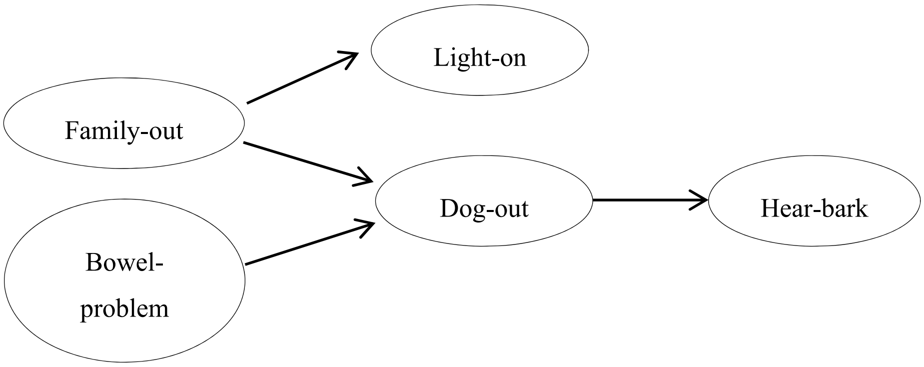


Figure 4.3 An example of BBN

Then, the prior probabilities of all root nodes (family-out and bowel-problem) and the conditional probabilities of all non-root nodes (light-on, dog-out, and hear-bark) must be given for a quantitative analysis. In the example the prior probabilities are given in Table 4.3 and the Conditional Probability Tables (CPTs) for other nodes are Table 4.4, Table 4.5 and Table 4.6.

Table 4.3 Prior probabilities for the root nodes

Family-out		Bowel-problem	
True	False	True	False
0.15	0.85	0.01	0.99

Table 4.4 CPT for dog-out node

Parents		$\Pr\left(Dog\text{-}out \middle| Parents\right)$	
Family-out	Bowel-problem	True	False
True	True	0.99	0.01
True	False	0.90	0.10
False	True	0.97	0.03
False	False	0.30	0.70

Table 4.5 CPT for light-on node

Parent	$\Pr\left(Light\text{-}on \middle| Parents\right)$	
Family-out	True	False
True	0.60	0.40
False	0.05	0.95

Table 4.6 CPT for hear-bark node

Parent	$\Pr\left(Hear\text{-}bark \middle| Parents\right)$	
Dog-out	True	False
True	0.70	0.30
False	0.01	0.99

Now, the conditional probabilities of the nodes can be calculated given some evidences (Charniak, 1991). For instance, if the family is out and the dog does not have bowel problems, the conditional probability of hear-bark will be 0.63. Joint probabilities can also be calculated using conditional probabilities, for example, the probability that the dog is out, the family is out, and the dog has bowel problems is 1.485×10^{-3}, using the following formula (a and c are the parents of b):

$$\mathrm{P(a, b, c)} = P(b|a,c) \cdot P(a) \cdot P(c)$$

Finally, independence assumptions must be kept in mind when carrying out quantitative analysis with a BBN. In short, “when there is no arc (link) between two nodes, this means that they are conditionally independent” (Rausand, 2011). One is explained by the relationship among family-out, dog-out and hear-bark in the example. If it is known that the dog is out, the probability that you can hear the dog barking is 0.7. It does not matter whether the family is out or not. Therefore, a node is assumed to be independent of its ancestors given the parents’ states. The other independence assumption is conditional independence between light-on and dog-out. They seem dependent because both are influenced by family-out, but they are assumed to be conditionally independent of each other when all their parents’ states are known. That is,

$$\begin{aligned}&\Pr(light-on\cap dog-out|family-out)\\&\qquad\qquad= Pr(light-on|family-out)\cdot Pr(dog-out|family-out)\end{aligned}$$

4.4 Event tree analysis

ETA is a method for modeling and analysis of accident scenarios. Hence, an event tree diagram presents the possible scenarios that may follow a specified hazardous event (Rausand, 2011). As ETA is used to describe the leak scenarios associated with work on isolated depressurized equipment in the Risk OMT model, it is a good tool to present the possible consequences of a hazardous event as well as the probability for each consequence.

4.4.1 Method description

The method is described by an example from Rausand (2011), shown in Figure 4.4.

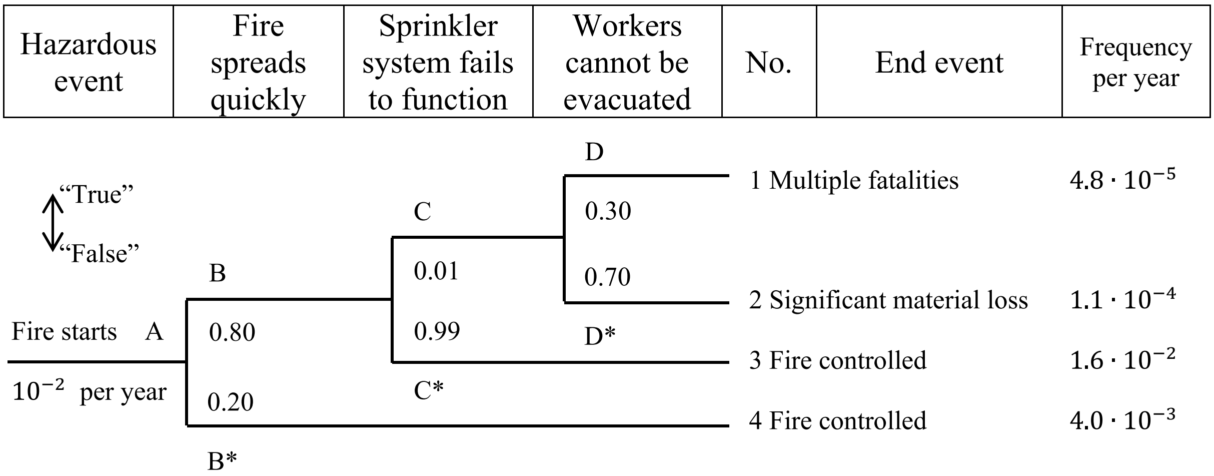


Figure 4.4 A simple event tree diagram

The tree starts with the hazardous event—the start of the fire in this example—and splits when specified pivotal events occur. Pivotal events listed as headings above the tree are usually failures of barriers or the events following the hazardous event. It is recommended that each pivotal event is expressed as a negative statement, as shown in Figure 4.4, so that the upper branch (“true”) goes to a serious end event. By this approach, the most serious accident scenarios will appear highest up in the event tree diagram (Rausand, 2011). Also, arranging pivotal events in the correct sequence is crucial because the results from the analysis will be wrong if the ordering is not correct (Rausand, 2011).

4.4.2 Quantitative analysis

Now, consider the quantitative use of ETA. The frequency of the hazardous event and the conditional probability of pivotal events are given to calculate the frequency of the various accident scenarios, as shown in Figure 4.4. For example, the frequency of Scenario 1: multiple fatalities, λ_1, can be calculated as follows:

$$\lambda_1 = \lambda_A \cdot \Pr(B \cap C \cap D) = \lambda_1 \cdot Pr(B|A) \cdot Pr(C|A \cap B) \cdot Pr(D|A \cap B \cap C)$$
$$= 10^{-2} \cdot 0.80 \cdot 0.01 \cdot 0.30 \approx 4.8 \cdot 10^{-5}\, per\ year$$

4.5 Fault tree analysis

“A fault tree is a logical diagram that displays the interrelationships between a potential critical event (accident) in a system and the causes for this event” (Rausand & Høyland, 2004, pp.96). FTA is one of the most commonly used techniques in risk and reliability studies, and also used in BORA-Release and the Risk OMT model. Rausand (2011), and Rausand and Høyland (2004) explain further how to construct a fault tree as well as its qualitative and quantitative use in risk studies. Detailed explanation of FTA is not provided in this thesis, since the model of this project will not use FTA.

5 BORA-Release and Risk OMT model

BORA-Release is a method for qualitative and quantitative risk analysis of the platform-specific HC leak frequency, and focuses mainly on safety barriers to prevent HC leaks and the influence of RIFs on the barriers (Aven et al., 2006). The Risk OMT model builds on previous work in the BORA-Release and operation condition safety (OTS) project, and emphasis is placed on a more comprehensive modeling of RIFs (Vinnem, 2014). Since this chapter chiefly describes how to model safety barriers for HC leaks and RIFs in BORA-Release and the Risk OMT model, the OTS project which presents a method for monitoring the status of operational safety barriers, will not be discussed further. A detailed description of the OTS project can be found in Sklet et al. (2010).

5.1 BORA-Release

BORA-Release consists of eight main steps, each of which will be described here. The description given here is based on Aven et al. (2006).

1) **Development of a basic risk model including HC release scenarios and safety barriers**

The development of a basic risk model starts from a HC leak scenario, and a set of 20 representative scenarios were developed in Sklet (2006). However, the recent and developed version of the set, the initiating events presented in Table 2.1 Overview of the initiating events in BORA (Vinnem, Seljelid, Haugen, & Husebø, 2007)Table 2.1 are considered in this thesis. Once it is decided to analyze an initiating event, one or more barrier functions for the initiating event are defined. Finally, the corresponding initiating event, barrier functions, and expected end events depending on the success or failure of the barrier functions are illustrated by a barrier block diagram. An example with the initiating event B3, valve(s) in incorrect position after maintenance, is shown in Figure 5.1.

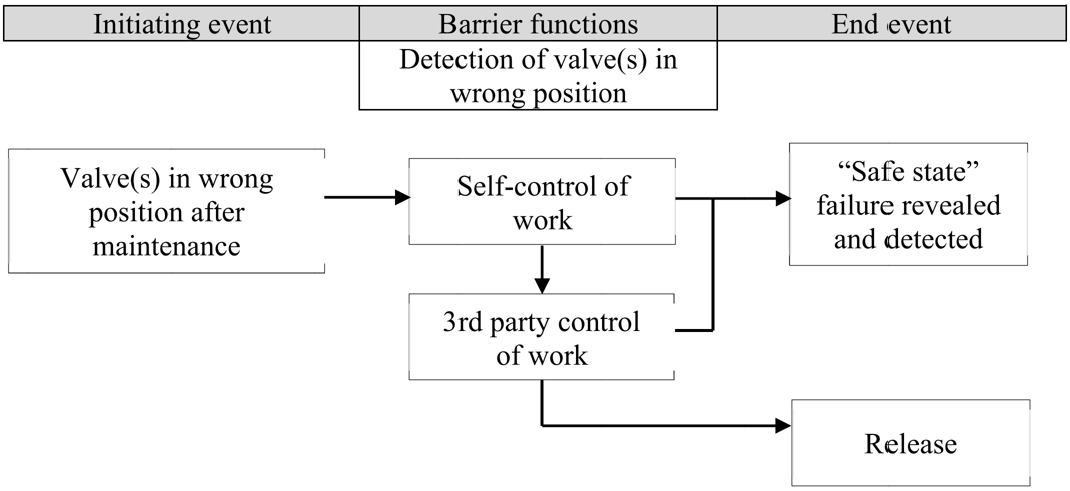


Figure 5.1 Barrier block diagram for a leak due to the initiating event B3 (Sklet et al., 2006)

2) Modeling the performance of safety barriers

The next step is to model the performance of safety barriers, in order to investigate the plant-specific barriers and the barriers performance. A fault tree with a barrier as a top event is developed for analysis of the barrier performance. For example, "failure to reveal valve(s) in wrong position after flowline inspection by self-control/use of checklists" can be a top event in case of the barrier, self-control of work, in Figure 5.1, and the events causing the top event consist of the fault tree. This is illustrated in Figure 5.2. The example presented in Figure 5.1 has two barriers, hence, another fault tree is needed for the other barrier, 3rd party control of work, to complete this step.

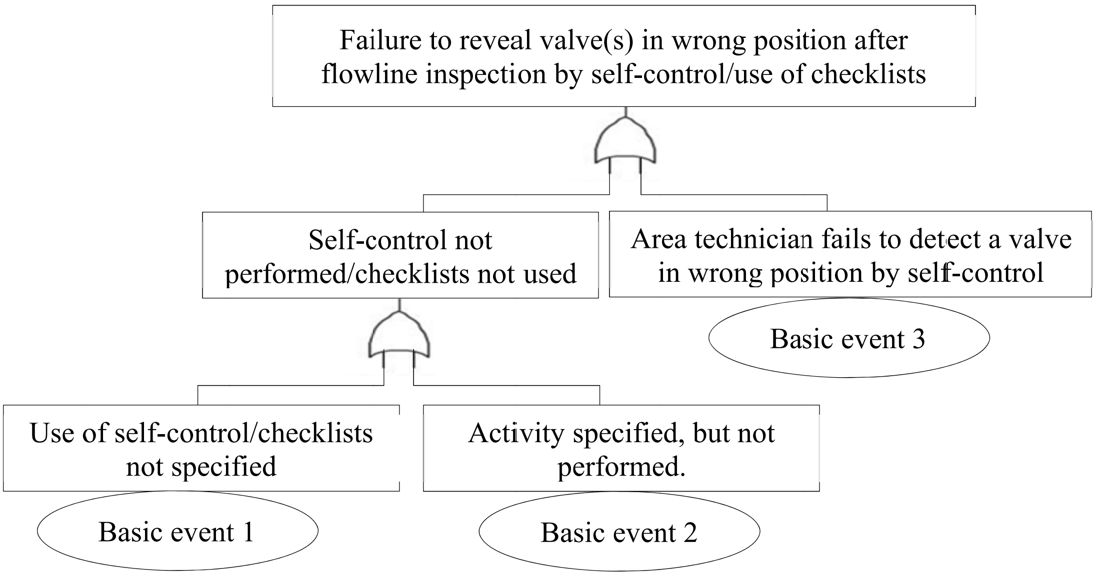


Figure 5.2 Fault tree for the barrier self-control of work (Sklet et al., 2006)

3) Assignment of generic input data and risk quantification based on these data

Step 3 assigns the frequency for the initiating event and probabilities for all the basic events in the fault trees. Industry-average data are generally used for this purpose, but plant-specific data are applicable if they are available.

4) Development of risk influence diagrams

Step 4 is to develop risk influence diagrams for the initiating events and all the basic events in the fault trees, which are assigned frequency/probability data in the previous step. Since the diagrams are used to modify the generic data assigned in the previous step (so that the modified frequencies represent the platform-specific frequencies), creating diagrams in this step is a core of BORA-Release. As shown in Figure 5.3, a maximum of six RIFs are located below the initiating event or basic event. The RIFs in the diagram are either selected from the generic RIFs in Table 4.1 or newly created if needed.

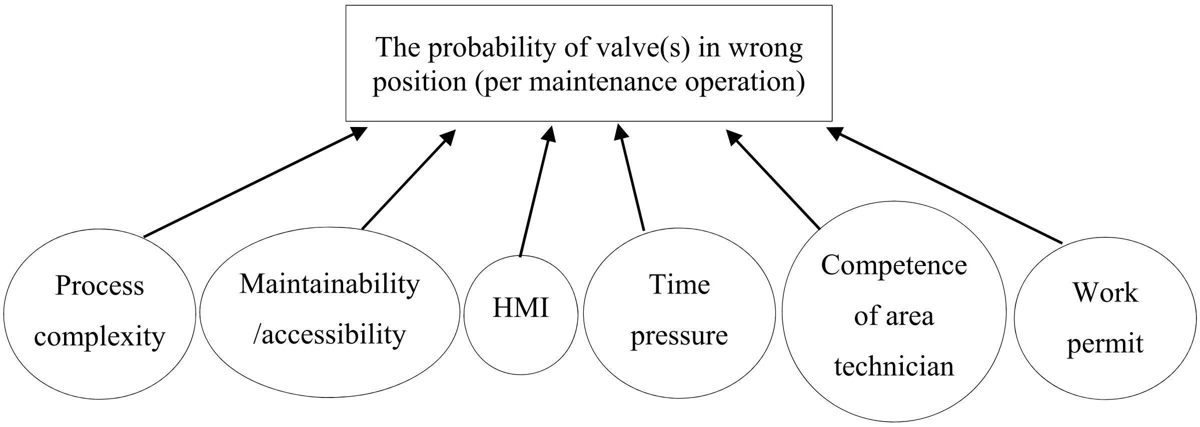


Figure 5.3 Risk influence diagram for the initiating event B3 (Sklet et al., 2006)

5) Scoring of risk RIFs

After the risk influence diagrams for the initiating event and the basic events are ready, a score is assigned to each identified RIF based on the assessment of the status of the RIFs on the platform. Each RIF is given a score from A to F, where score A corresponds to the best standard in the industry, C to average, and F to worst practice.

6) Weighting of risk RIFs

Weighting of RIFs is also necessary along with scoring, in order to convert generic data to platform-specific data. Weights represent the influence of the RIFs on the frequency of occurrence of the initiating event or basic event. The most important RIF is given a relative weight equal to 10 and the other RIFs are given relative weights on the scale 10-8-6-4-2. Finally the weights are normalized as the sum of the weights for the RIFs influencing an initiating event or basic event should be equal to one.

7) Adjustment of generic input data

If all the data including generic frequencies/probabilities and scores and weights for the RIFs are determined, then the platform-specific probability of occurrence of Event A, $P_{rev}(A)$, is calculated as follows: (To distinguish frequency and probability, F_{rev} will be used for the frequency of an initiating event.)

$$P_{rev}(A) = P_{ave}(A) \cdot \sum_{i=1}^{n} w_i Q_i$$

Here, $P_{ave}(A)$ denotes the industry-average (or generic) probability of occurrence of Event A. w_i and Q_i respectively denote the weight of and the numerical measure of the score of RIF No. i for Event A. n is the number of RIFs. For w_i, the normalized weight remains intact, and the way to determine Q_i from the score on the scale A to F is explained in detail in Aven et al. (2006).

8) Recalculation of the risk in order to determine the platform-specific risk

Finally, the platform-specific frequency of an HC leak scenario is calculated by applying the platform-specific frequency/probabilities for the initiating event and all events in the risk model. For instance, the frequency of an HC leak due to the initiating event B3, valve(s) in incorrect position after maintenance, is estimated at 0.0414696, based on the frequency of the initiating event and the probabilities of the events in the risk model, as shown in Figure 5.4. The frequency/probabilities are calculated based on those of the basic event. The probability calculation of an event in the risk model from its basic events is shown in Figure 5.5. This is the same example from Step 2 that was presented in Figure 5.2.

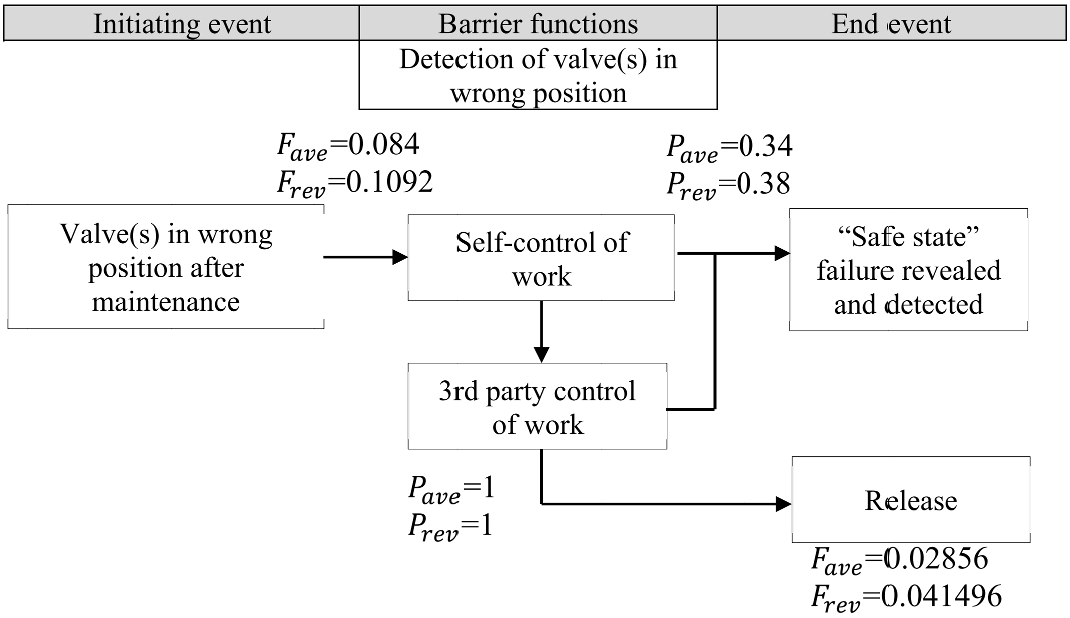


Figure 5.4 Generic/platform-specific frequencies of an HC leak due to initiating event B3 (Sklet et al., 2006)

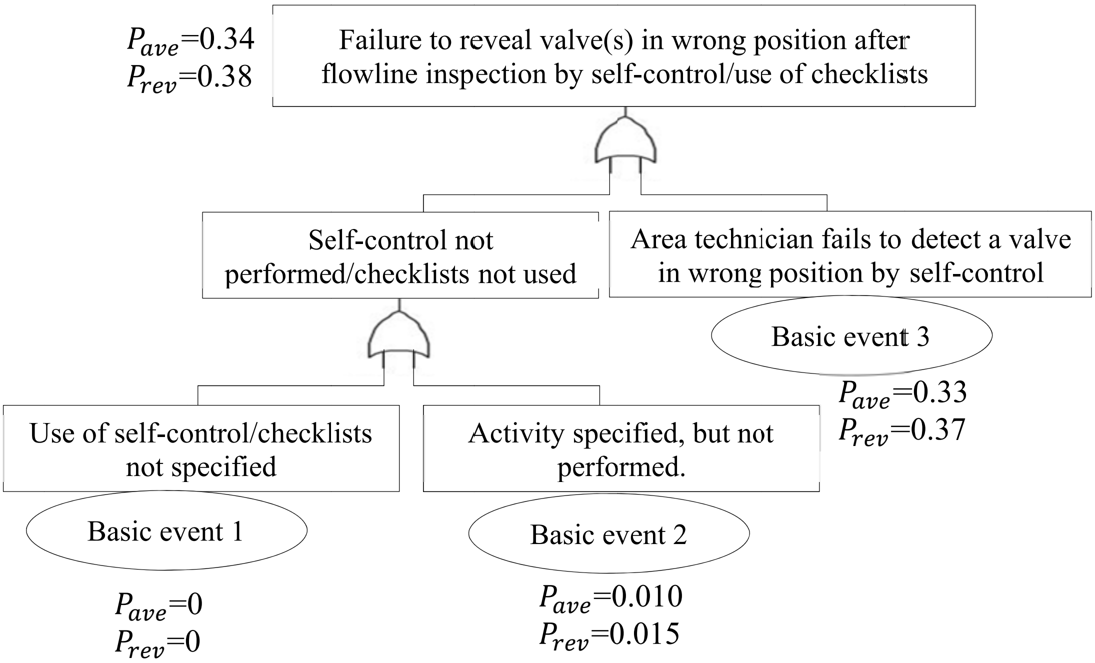


Figure 5.5 Probability calculation of an event in the risk model (Sklet, Vinnem, & Aven, 2006)

5.2 Risk OMT model

As a developed model of BORA-Release, the Risk OMT model is more structured and systematic in terms of the representation of leak scenarios and risk influence diagrams, whereas the model only deals with the leak due to the initiating types B and C, which are associated with human intervention (see Table 2.1 for details). The explanation of the Risk OMT model given here is based on Vinnem et al. (2012)

First, an event tree, rather than a barrier block diagram, is used to show leak scenarios. The event tree including the initiating events, B1, B2, B3, and B4, is developed and presented in Figure 5.6. Unlike BORA-Release, several relevant initiating events are modeled together in an event tree so that the leak scenarios reflect the actual events sequence leading to a leak.

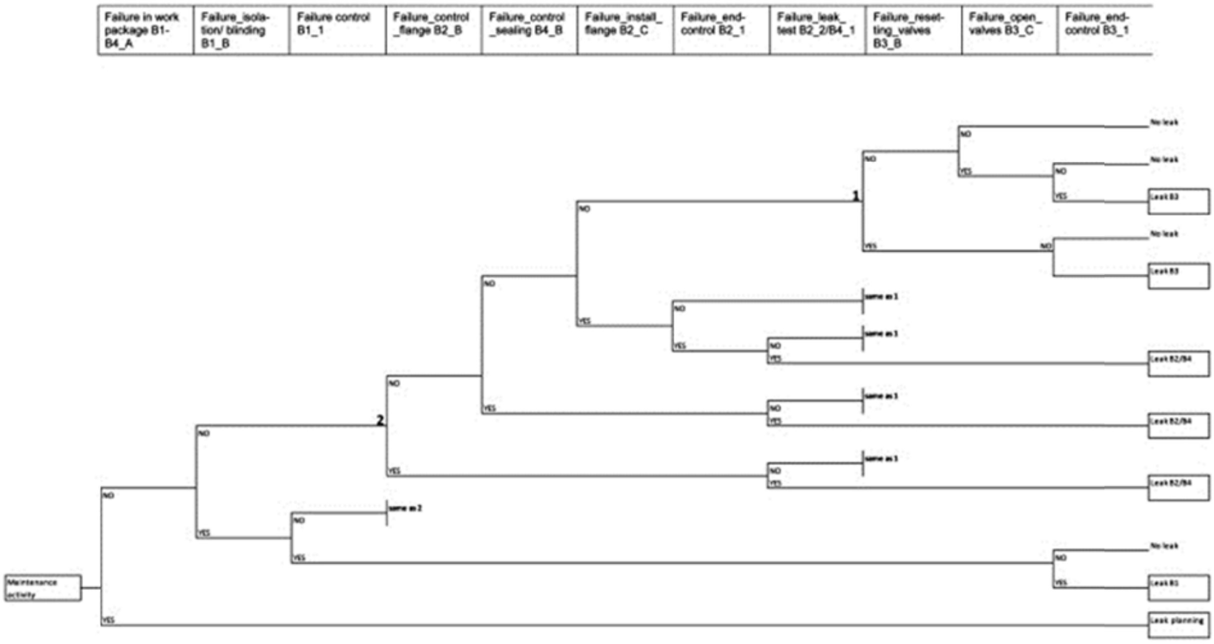


Figure 5.6 Event tree describing the leak scenarios associated with the initiating events B1-B4 (Vinnem et al., 2012)

Then, fault trees for all the events in an event tree are established, similarly as in BORA-Release. The difference is that all the fault trees of the Risk OMT model are similarly structured, as shown in Figure 5.7 which shows a fault tree for the first event in Figure 5.6. The top event in a fault tree is considered to be divided into failures in planning and control phases, and then further divided into failures of omission and execution. Also, failures of execution are further examined in terms of violation, mistake, and slips and lapses in the present model; failures of omission are not, because failures of execution are considered more important than failures of omission in the case of leaks. So, the basic events are failure of omission, violation, mistake, and slips and lapses in both the planning and control phases.

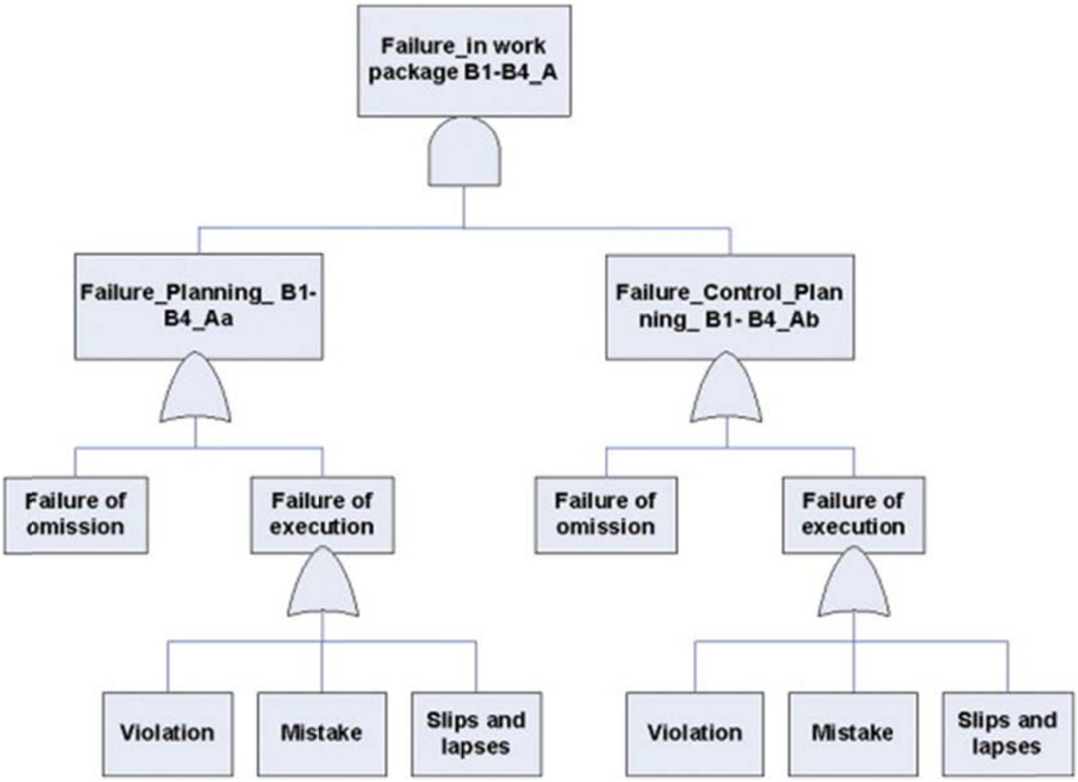


Figure 5.7 Fault tree model for B1-B4.A failure in work package (Vinnem et al., 2012)

Risk influence diagrams are also developed for the basic events; however, the Risk OMT model has two generic diagrams for the planning and control phases that can be used for all the basic events. Therefore, there is no need to develop a risk influence diagram for a basic event each time. The generic diagram for the control phase is presented in Figure 5.8.

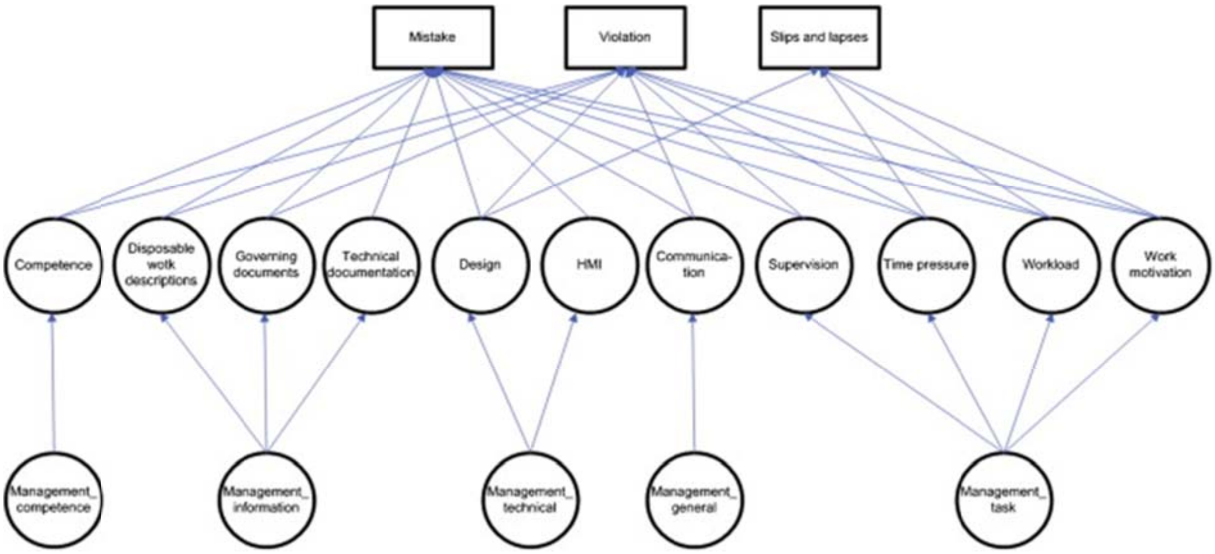


Figure 5.8 Generic RIF model for execution and control activities (Vinnem et al., 2012)

A distinct difference between the risk influence diagram in BORA-Release and that in the Risk OMT model is that the risk influence diagram of the Risk OMT model has two leveled RIFs, whereas there is only one level in BORA-Release. RIFs on the second level are of a more managerial nature, such as competence management and technical management.

Overall concepts, such as scores and weights for RIFs to calculate platform-specific HC leak frequencies, are still used in the Risk OMT model; however, the calculation method is more systematic in dealing with the increased number of RIFs in a risk influence diagram compared to BORA-Release. First, scores (or states) and weights of RIFs on the second level are determined depending on the condition of the specific platform. Then, the conditional probabilities that a RIF on the first level has a certain state are calculated using triangular distribution based on the determined scores and weights of RIFs on the second level. Further, the mean state of a RIF on the first level, based on the conditional probabilities, is equal to the state it is affected by. For instance, technical management on the second level in Figure 5.8 influences two RIFs on the first level—design and HMI. If it is assumed that the state of technical management is B, then the expected states of design and HMI are also B. However, the conditional probability distributions for two RIFs are not always the same. Variances differ depending on how much influence the parent RIF on the second level will have on a child RIF on the first level. As shown in Figure 5.9, high dependency on the parent RIF has a distribution with a narrow variance around the modal value (blue), and low dependency with a wider variance (green).

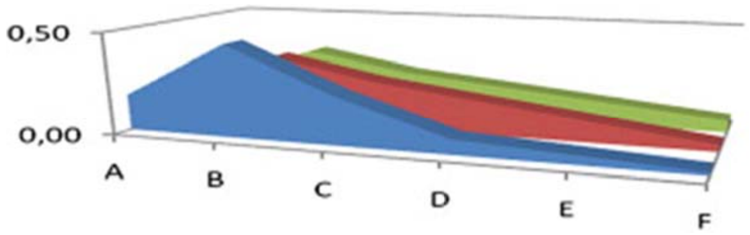


Figure 5.9 The CPT for a RIF given "RIF Level 2 in State B" for the cases that the dependency is low (green), medium (brown), and high (blue). (Vinnem et al., 2012)

After the CPTs for all the RIFs on the first level influencing basic events (such as mistake, violation, and slips and lapses) are determined, multiple CPTs for a basic event are established for all possible state combinations of the RIFs on the first level. In case of slips and lapses, there are four RIFs—design, time pressure, work load, and work motivation—that influence the basic event, and then $6^4 = 1296$ CPTs are made (because four RIFs have six states each). Then, as explained in Chapter 4.3.2, joint probabilities are calculated. Finally, the probabilities that the state of slips and lapses is A, B, … or F are estimated by summing up the joint probabilities. However, this is not the end, because the calculated probabilities are not the probability that slips and lapses occur but the probabilities that the condition to prevent slips and lapses is best (A), average (C), or worst (F). Therefore, one more step is needed to get the probability that a basic event (human error such as slips and lapses) occurs. Table 5.1 shows how to estimate the probability that a basic event occurs given that calculated probabilities of a basic event in states A-F are a-f. Here, average Human Error Probability (HEP) of 0.01 is chosen (so, the HEP for State C is 0.01), and an error fraction of three is used. The HEP for different error fractions can be found in Table 5.2.

Table 5.1 A basic event probability estimation given probabilities for the states and HEPs

	Probabilities	Human error probabilities (HEP)
P(state of a basic event = A)	a	0.0011
P(state of a basic event = B)	b	0.0033
P(state of a basic event = C)	c	0.0100
P(state of a basic event = D)	d	0.0173
P(state of a basic event = E)	e	0.0300
P(state of a basic event = F)	f	0.0520
P(a basic event occurs)	0.0011a+0.0033b+0.0100c+0.0173d+0.0300e+0.0520f	

Table 5.2 Interpretation of an HEP = 0.01 value for different error fractions (Vinnem et al., 2012)

State / Error fraction	A	B	C	D	E	F
3	0.0011	0.0033	0.0100	0.0173	0.0300	0.0520
5	0.0004	0.0020	0.0100	0.0224	0.0500	0.1118
10	0.0001	0.0010	0.0100	0.0316	0.1000	0.3162

As described so far, the calculation is complex and cannot be solved manually for an entire diagram. Hence, the use of software, including HUGIN (Andersen, Olesen, Jensen, & Jensen, 1989), becomes necessary. Probability calculations after basic events are performed in the same way in BORA-Release, so refer to Chapter 5.1.

6 Investigation of HC leak incidents

This thesis presents a model for non-operational leaks (not caused by human interventions), which were not modeled in the Risk OMT model, and investigation on those leaks has to be preceded for modeling. This chapter focuses on the investigation of 25 leaks that occurred in Norway, the UK, and the USA, classified with their initiating events. The leaks are described in brief at first, and probed with events and causal factors charting (see Chapter 3.2).

The sources of information are the PSA and the Norwegian Oil and Gas Association for leaks in Norway, the Step Change in Safety for leaks in the UK, and the Bureau of Safety and Environmental Enforcement (BSEE) for leaks in the USA. Exact date and platform name are not provided for some because the sources describe the incidents anonymously. In addition, event sequences for some cases are quite limited due to lack of information in the sources.

6.1 Degradation of valve sealing (A1)

03500

The description and event and causal factors charting of the incident is based on the report from Step Change in Safety (2014h). Since the exact platform is not presented in the source, the incident is recorded as its alert ID, 03500. The alert ID is the number used to identify an incident in Step Change in Safety, a non-profit organization that aims to make the UK the safest place to work in the global oil and gas industry.

During preparation for the platform startup in the UKCS, an operator detected minor emission from a shutdown valve in the gas export to gas lift manifold on August 7, 2013. At the time of the incident, the valve was in the closed position and the pressure in line was 13 bar, which is significantly below the design operation pressure of 145 bar. The direct cause of the incident was degradation of the O rings on the stem seal of the valve, initiating event A1.

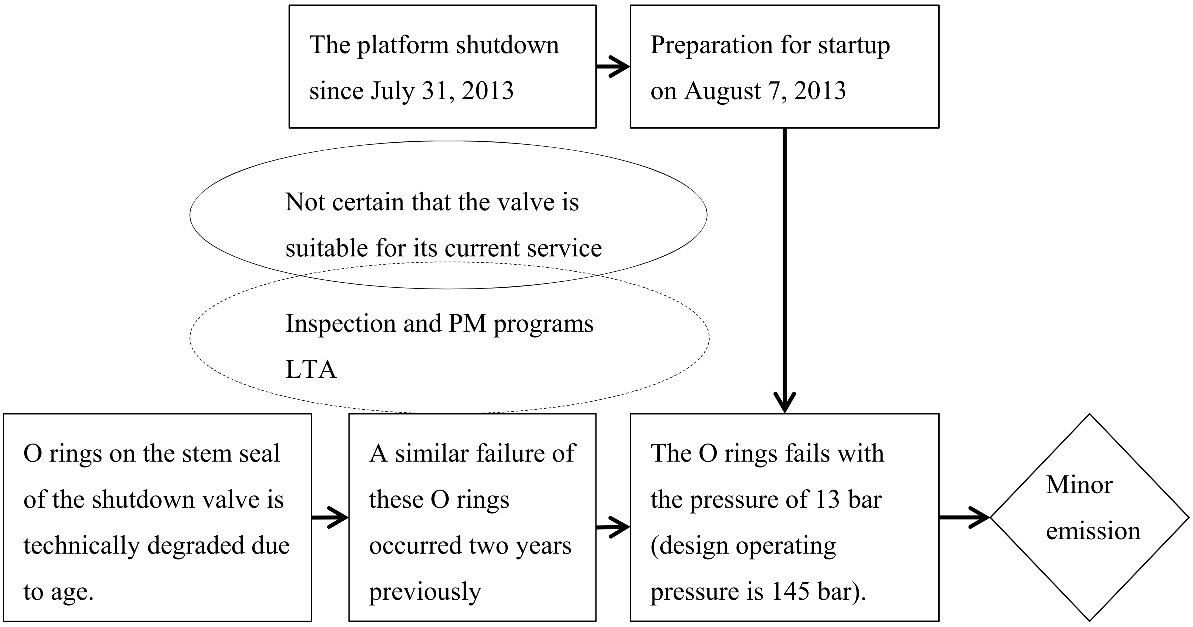


Figure 6.1 Event and casual factors chart of 03500

03584

The description and event and causal factors charting of the incident is based on the report from Step Change in Safety (2015). Since the exact platform is not presented in the source, the incident is recorded as its alert ID, 03584.

On Thursday, June 6, 2013, an operator detected the smell of gas and further investigation found a leak from the common injection header isolation valve stem to the gearbox flange, on a platform in the UKCS. It was revealed that the leak originated in the valve stem seal arrangement, due to the failure of one or more of the stem seal O rings. Thus, the initiating event is A1 degradation of valve sealing. Events causing the seal failure are not provided in the source, but the inadequate maintenance program of the platform is considered as the prior event, judging from the lessons identified and recommendation.

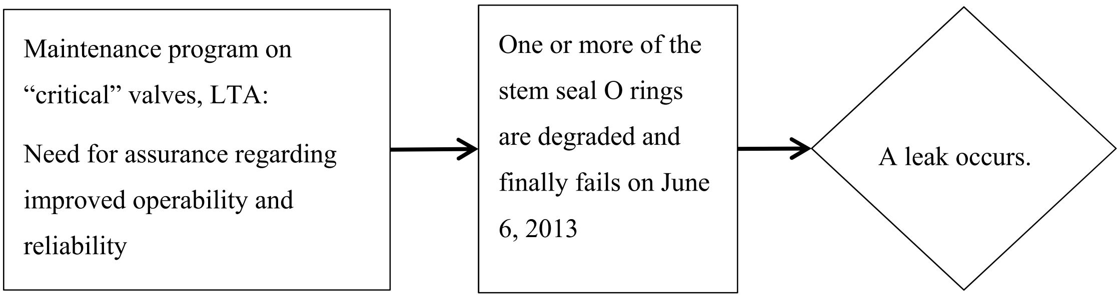


Figure 6.2 Event and casual factors chart of 03584

6.2 Degradation of flange gasket (A2)

Unnamed 1

The description and event and causal factors charting of the incident is based on the report from the Norwegian Oil and Gas Association (2014c). Since the exact platform and date of the incident is not presented in the source, the incident is recorded as Unnamed 1. Detailed explanation of only the causes is provided.

A gas leak occurred in a pig launcher on a platform in the NCS in 2013. This incident was due to the degraded gasket in the pig launcher door in connection with the unintended opened valves between the pig launcher and an expert manifold. So, the initiating event type is A2. As a result, a gas leak at approximately 0.8kg/s lasted for one to three minutes and total emissions were around 150 kg.

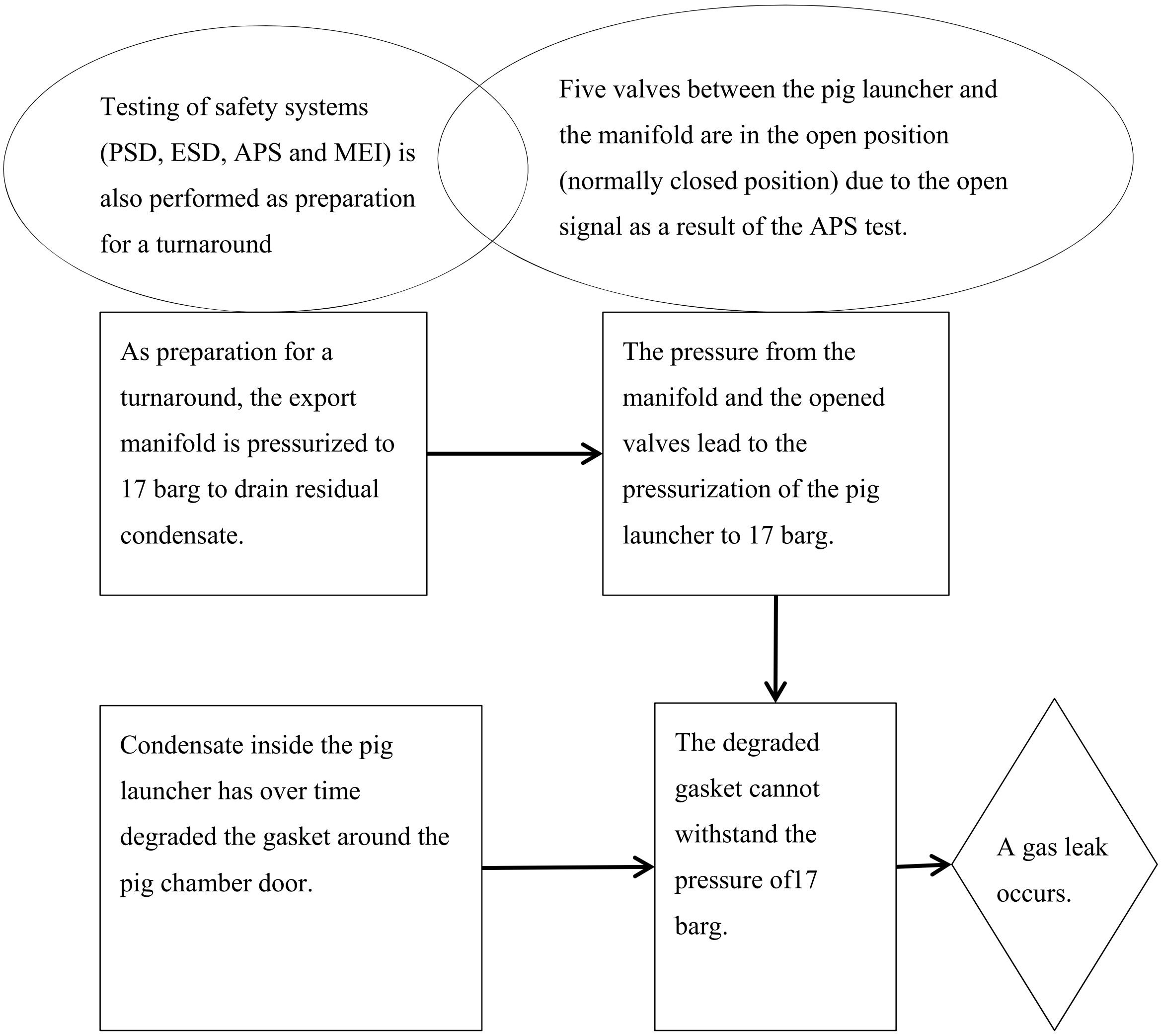


Figure 6.3 Event and casual factors chart of Unnamed 1

6.3 Loss of bolt tensioning (A3)

Valhall PCP

The description and event and causal factors charting of the incident is based on the report from the PSA (2004).

A gas leak was discovered by a valve technician from a not-tight grease nipple on a 20" sectioning valve on the Valhall Production and Compression Platform (PCP) in the NCS on January 12, 2004. The leak is classified as an A3 type initiating event that is due to the loss of bolt tensioning, since the leaky nipple was the direct cause. However, why the nipple remained not tight was not revealed. The total volume of released gas was $25m^3$ and the maximum leak rate was 0.18kg/s. The platform was shut down for five hours but no injuries were reported.

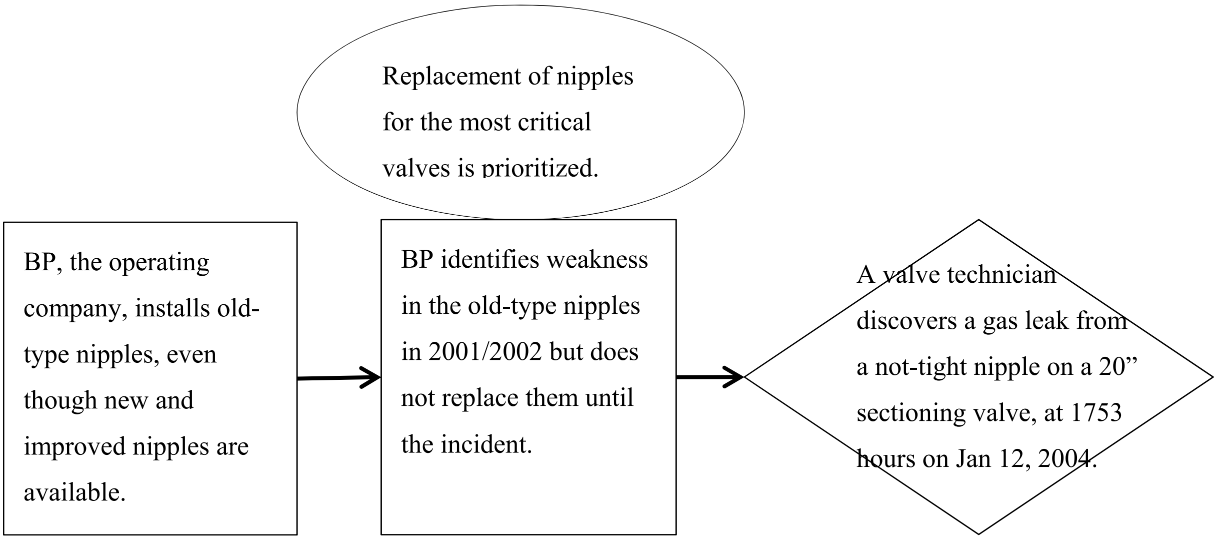


Figure 6.4 Event and casual factors chart of Valhall PCP

6.4 Fatigue (A4)

03518

The description and event and causal factors charting of the incident is based on the report from Step Change in Safety (2014g). Since the exact platform is not presented in the source, the incident is recorded as its alert ID, 03518.

A leak from an oil export temperature probe on a fixed production in the UKCS was reported on December 1, 2013. The leak is due to the fatigue failure of the thermowell, the initiating type A4. The process change increased vibration by oil flow, leading to cracks and, finally, to failure. The oil export system was shutdown, and the total amount of released oil was 8.7 kg.

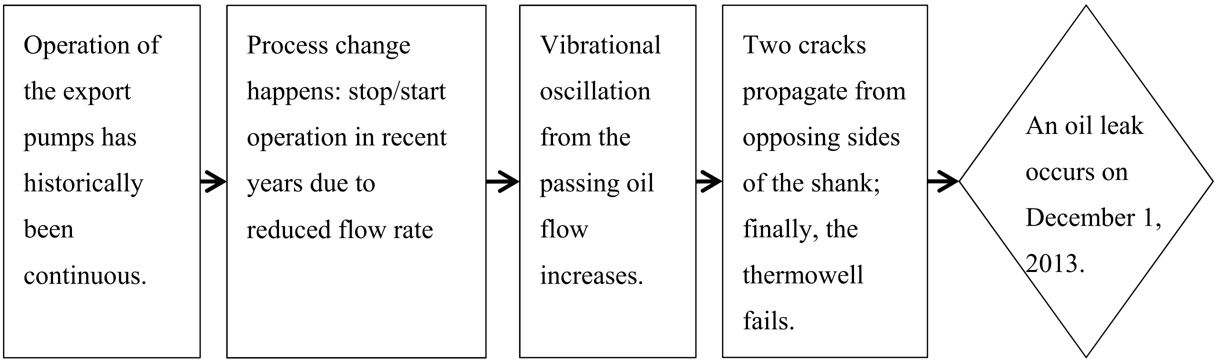


Figure 6.5 Event and casual factors chart of 03518

Ship Shoal 209, Platform A-AUX

The description and event and causal factors charting of the incident is based on the report from the BSEE (2010). Due to the lack of information in the source, the description and events and causal factors chart are rather limited in this incident.

On September 14, 2010 at approximately 0500 hours, an operator noticed a leak at the top of the heater treater fire tube on Platform A-AUX, located in Ship Shoal block 209, Gulf of Mexico, U.S.A. The leak resulted from an 8” long crack in the tube, due to fatigue. Thus, the initiating event of this incident is A4, fatigue. As a result, approximately 4.71 barrels of oil traveled down the side of the vessel and went overboard. No injuries were reported.

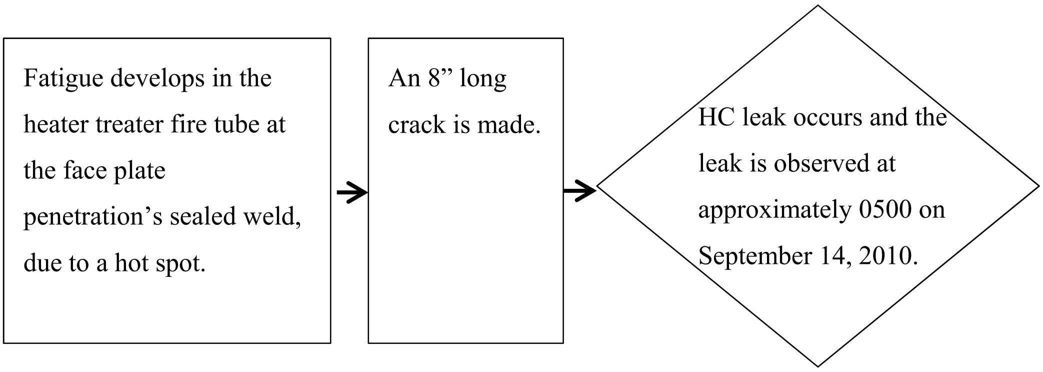


Figure 6.6 Event and casual factors chart of Ship Shoal 209, Platform A-AUX

Unnamed 2

The description and event and causal factors charting of the incident is based on the report from the Norwegian Oil and Gas Association (2014a). Since the exact platform and date of the incident is not presented in the source, the incident is recorded as Unnamed 2. Detailed explanation of only the causes is provided.

Gas was released from a High-Pressure (HP) reciprocating compressor valve on a platform on the NCS in 2013. Five of the eight bolts on the valve cover broke due to the initiating event type A4 fatigue, which led to the gas leak. The amount of released gas was 390 - 450 kg and the production immediately shut down.

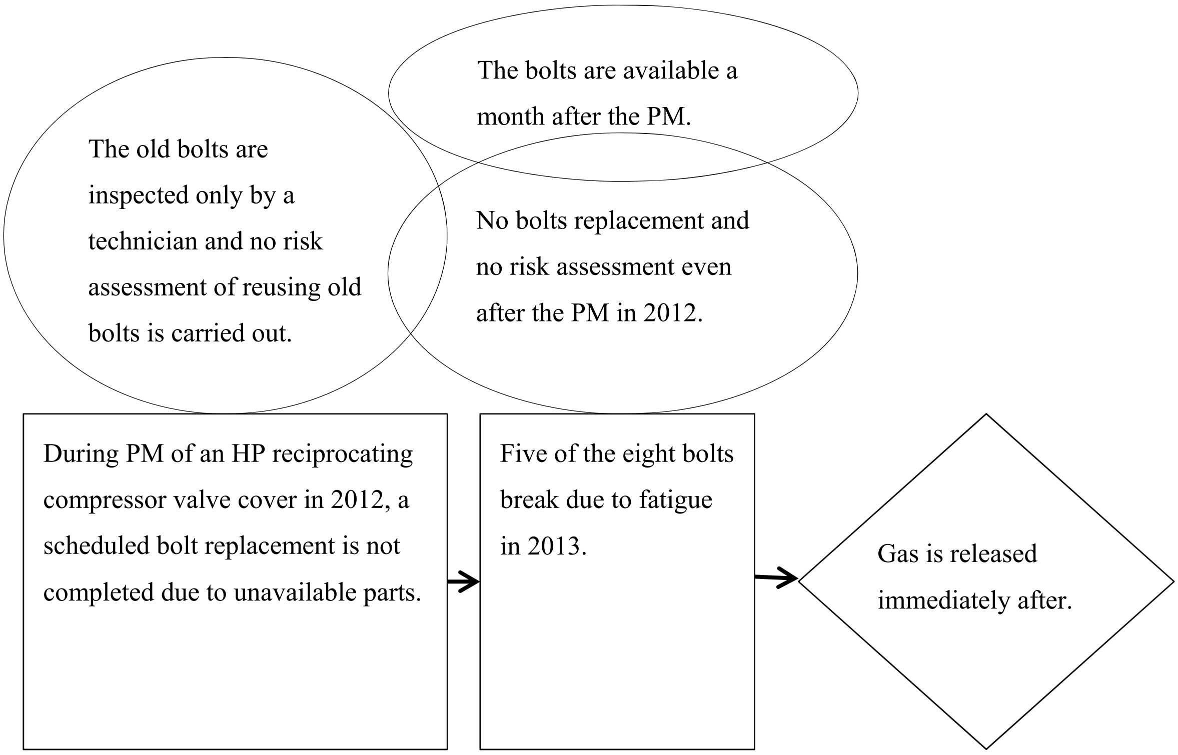


Figure 6.7 Event and casual factors chart of Unnamed 2

6.5 Internal corrosion (A5)

03522

The description and event and causal factors charting of the incident is based on the report from Step Change in Safety (2014b). Since the exact platform is not presented in the source, the incident is recorded as its alert ID, 03522.

A pinhole leak occurred on an HP gas compressor recycle line on an FPSO unit in the UKCS on July 31, 2013. The initiating event A5 internal corrosion (preferential weld corrosion) caused the failure at the junction of carbon steel and duplex pipe work, thus leading to the leak. 6.78kg of methane gas was released.

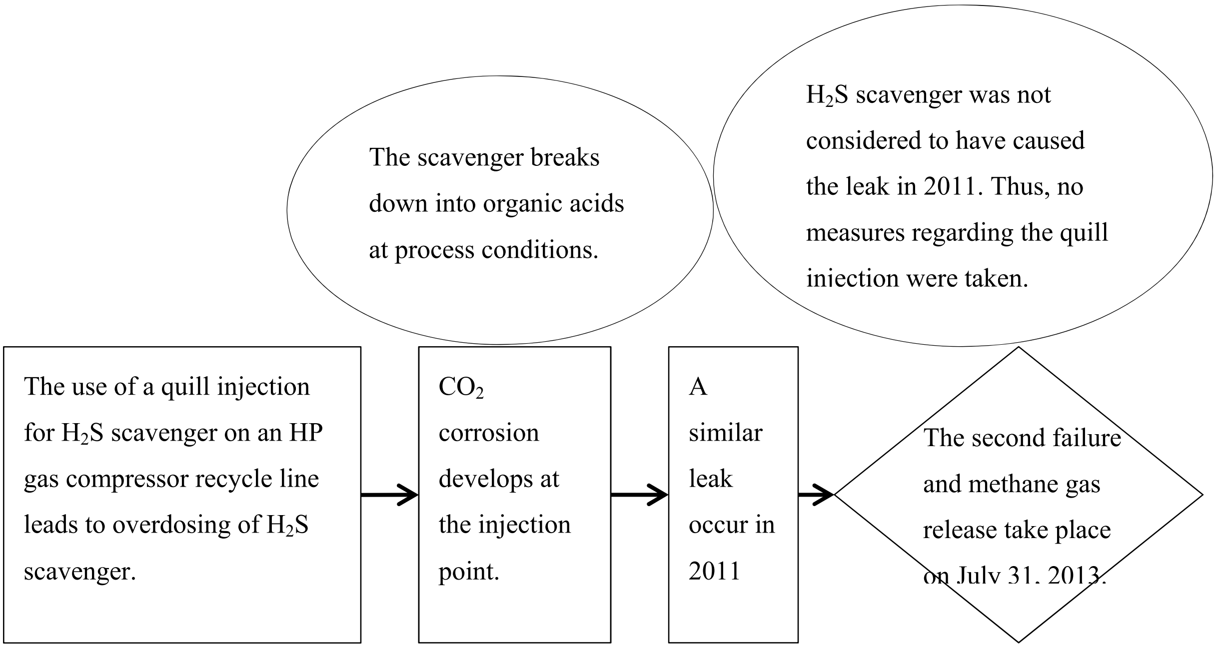
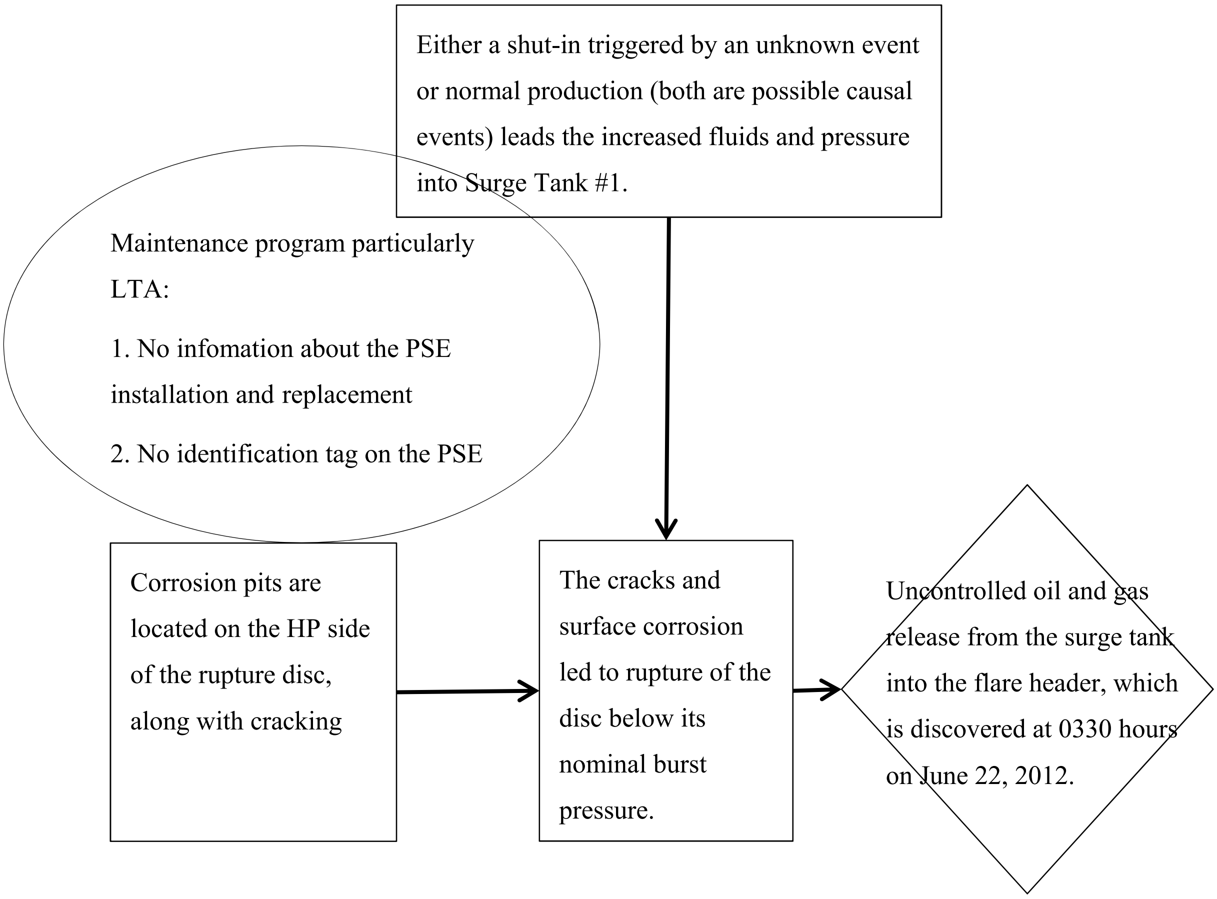


Figure 6.8 Event and casual factors chart of 03522

6B 5163 Houchin

The description and event and causal factors charting of the incident is based on the report from the BSEE (2013).

An incident occurred on platform Houchin in the Santa Barbara Channel, offshore the State of California, on June 22, 2012, commencing between the hours of 0100 and 0300. It started with the flow of oil and gas out of Surge Tank No. 1, and resulted in a pollution event. Oil and gas initially flowed out of the surge tank, because a Pressure Safety Element (PSE), a rupture disc on the surge tank, did not hold the increased pressure in the tank. The investigation team did not have enough information about what had caused the pressure increase in the valve. Nevertheless, they revealed how the PSE had failed even though the pressure had been below its nominal rupture pressure. Accordingly, the sequence to the failure of the PSE is treated as the main events sequence in the events and causal factors chart for the investigation. The cause of the failure was due to corrosion and crack on the rupture disc, the initiating event A5, internal corrosion.



Either a shut-in triggered by an unknown event or normal production (both are possible causal events) leads the increased fluids and pressure into Surge Tank #1.

Maintenance program particularly LTA:

1. No infomation about the PSE installation and replacement

2. No identification tag on the PSE

Corrosion pits are located on the HP side of the rupture disc, along with cracking

The cracks and surface corrosion led to rupture of the disc below its nominal burst pressure.

Uncontrolled oil and gas release from the surge tank into the flare header, which is discovered at 0330 hours on June 22, 2012.

Figure 6.9 Event and casual factors chart of 6B 5163 Houchin

Hermosa

The description and event and causal factors charting of the incident is based on the report from the BSEE (2000).

A sour gas release occurred on the Hermosa platform located in California's Santa Maria Basin on August 3, 1999. The gas leak arose from a ruptured elbow in an 8” HP gas flowline, and the rupture was because of internal corrosion, which is initiating event A5. The released gas had an H2S concentration of about 18000 ppm. No one was harmed in the incident.

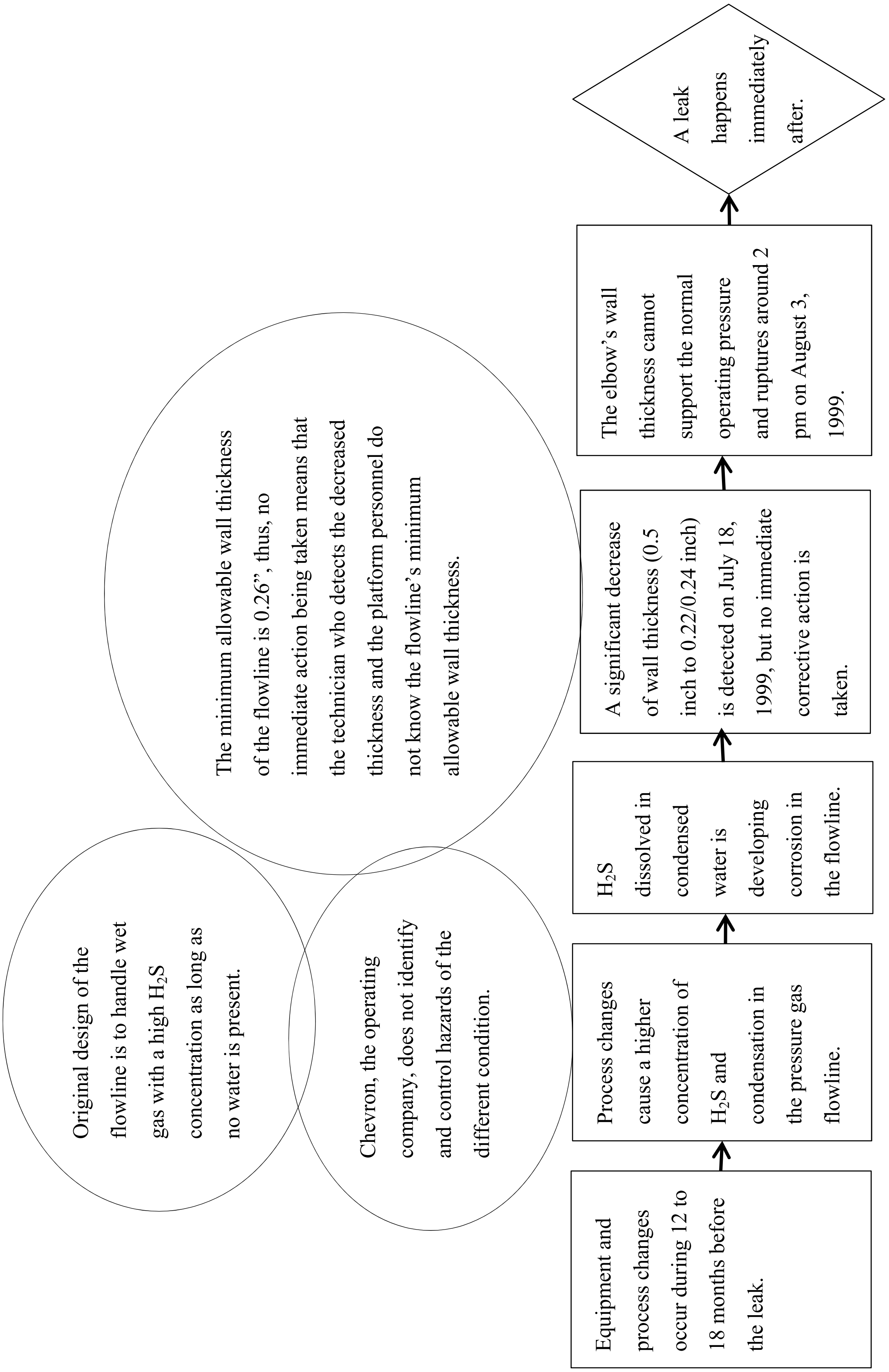


Figure 6.10 Event and casual factors chart of Hermosa

Ula P

The description and event and causal factors charting of the incident is based on the report from the PSA (2013).

A HC leak occurred on the Ula P (production) platform located in the southern Norwegian section of the North Sea on September 12, 2012. The leak arose in a bypass valve installed on a produced water outlet from the HP inlet separator. The direct cause of the leak was fracturing of the bolts holding the valve together. The leak is classified as initiating event type A5, internal corrosion, because the fracture resulted from internal corrosion of the bolts exposed to produced water with a high content of chlorides and a temperature of 120℃. The amount of HC leak is estimated at 20 cubic meters of oil and 1600 kg of gas, which is substantial. No people were injured in the incident, but the PSA considers that the incident had the potential to become a major accident.

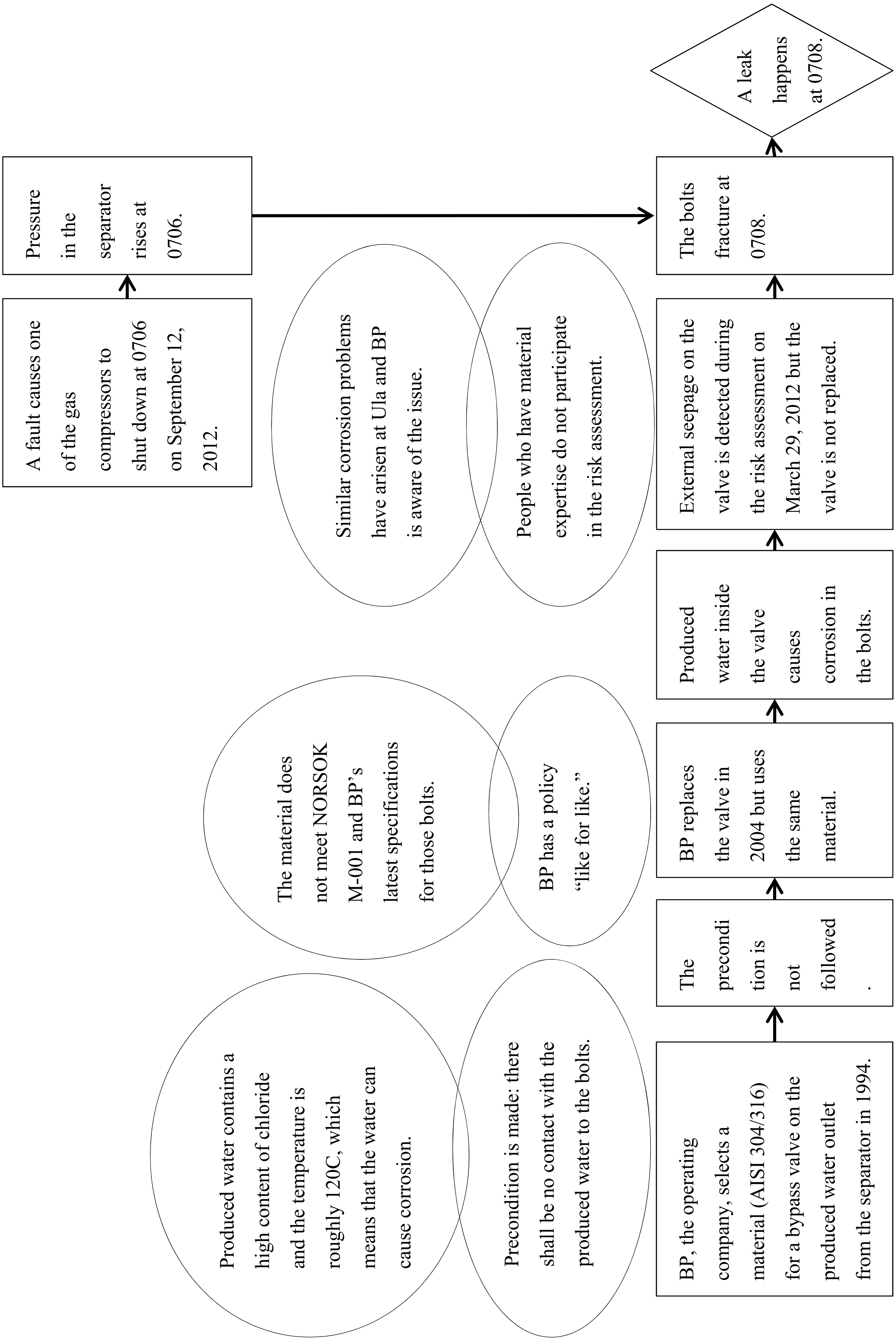


Figure 6.11 Event and casual factors chart of Ula P

6.6 External corrosion (A6)

03484

The description and event and causal factors charting of the incident is based on the report from Step Change in Safety (2014d). Since the exact platform is not presented in the source, the incident is recorded as its alert ID, 03484.

The failure of small bore instrument tubing (12mm diameter, thick wall, stainless steel) forming part of a flow transmitter arrangement in the oil export system on a fixed production platform happened on May 7, 2013. As a consequence, a small amount of crude oil leaked onto the deck. Severe pitting and stress corrosion cracking fractured the tubing; thus, the initiating event is A6, external corrosion. The chemical mechanism leading to corrosion is not clarified in the source. However, the management of change in 2007 contributed to the environment becoming one where corrosion is easily initiated, due to inadequate maintenance and inspection routines.

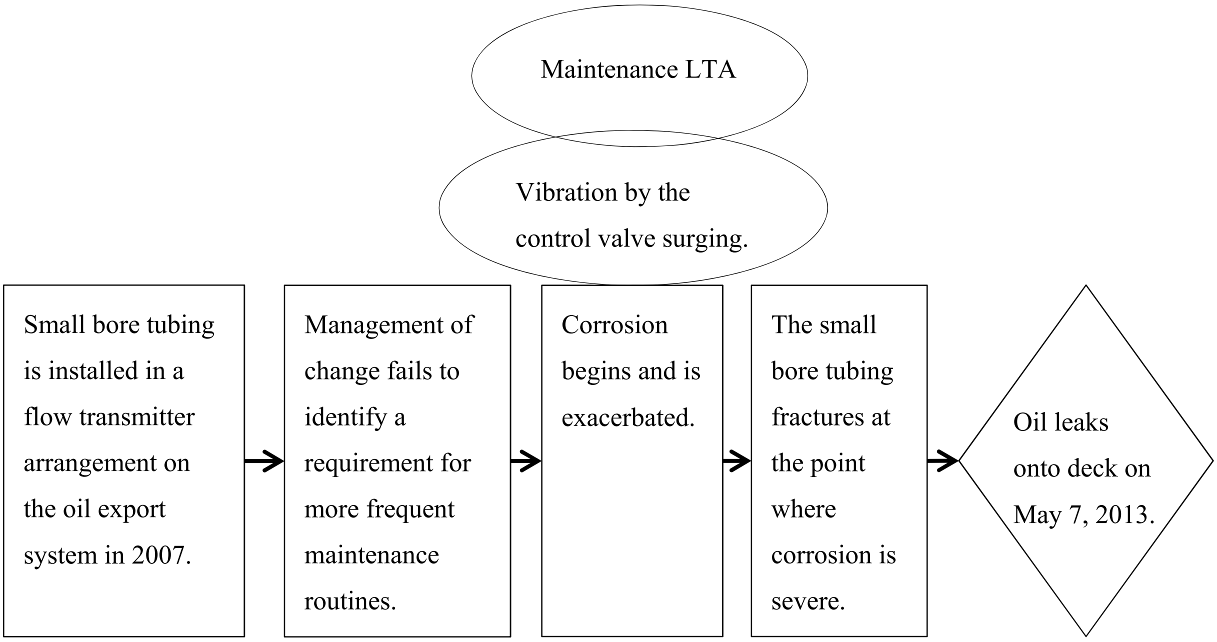


Figure 6.12 Event and casual factors chart of 03484

03527

The description and event and causal factors charting of the incident is based on the report from Step Change in Safety (2014c). Since the exact platform is not presented in the source, the incident is recorded as its alert ID, 03527.

The incident took place on November 14, 2012. A technician initially found a small puddle of oil on the deck below a test separator on a fixed production platform, later, oil was identified to be coming from the 4” line which is a balance line between the production separator and coalesce. The leak from the pipe line is due to the initiating event A6 external corrosion, but it is an unusual type in terms of corrosion of a Corrosion-Resistant Alloy (CRA). The process was shutdown for repairing, but the consequences were minor.

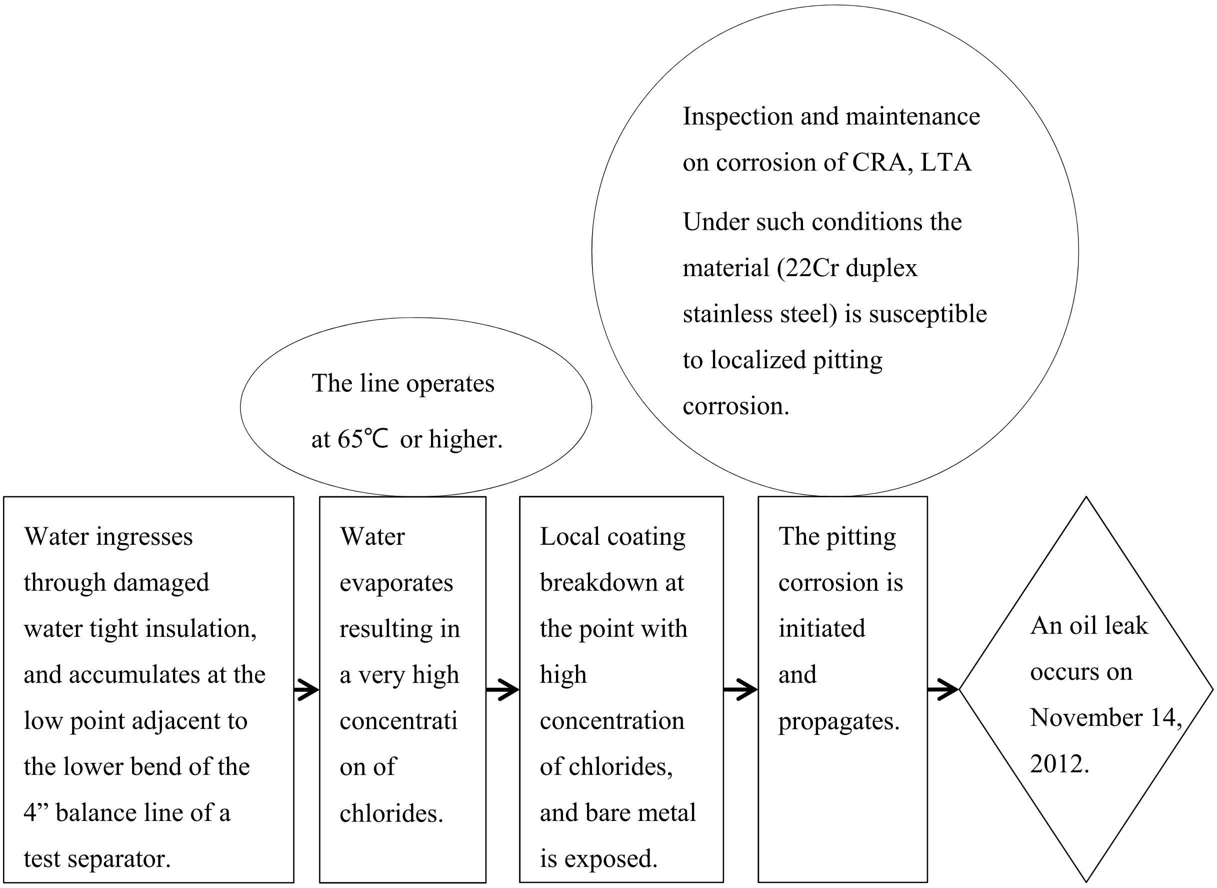


Figure 6.13 Event and casual factors chart of 03527

03534

The description and event and causal factors charting of the incident is based on the report from Step Change in Safety (2014f). Since the exact platform is not presented in the source, the incident is recorded as its alert ID, 03534.

On August 10, 2013, an operator became aware of a noise in the area of the third-stage compression on a semi-submersible production platform in the UKCS. While checking the area, it was found that the noise was due to the leak on a small bore tubing impulse line associated with the third-stage of the gas compressor. It was due to corrosion-assisted fatigue cracking; thus, the initiating event is A6 external corrosion. To fix the tubing, production was shutdown and blow down was manually initiated.

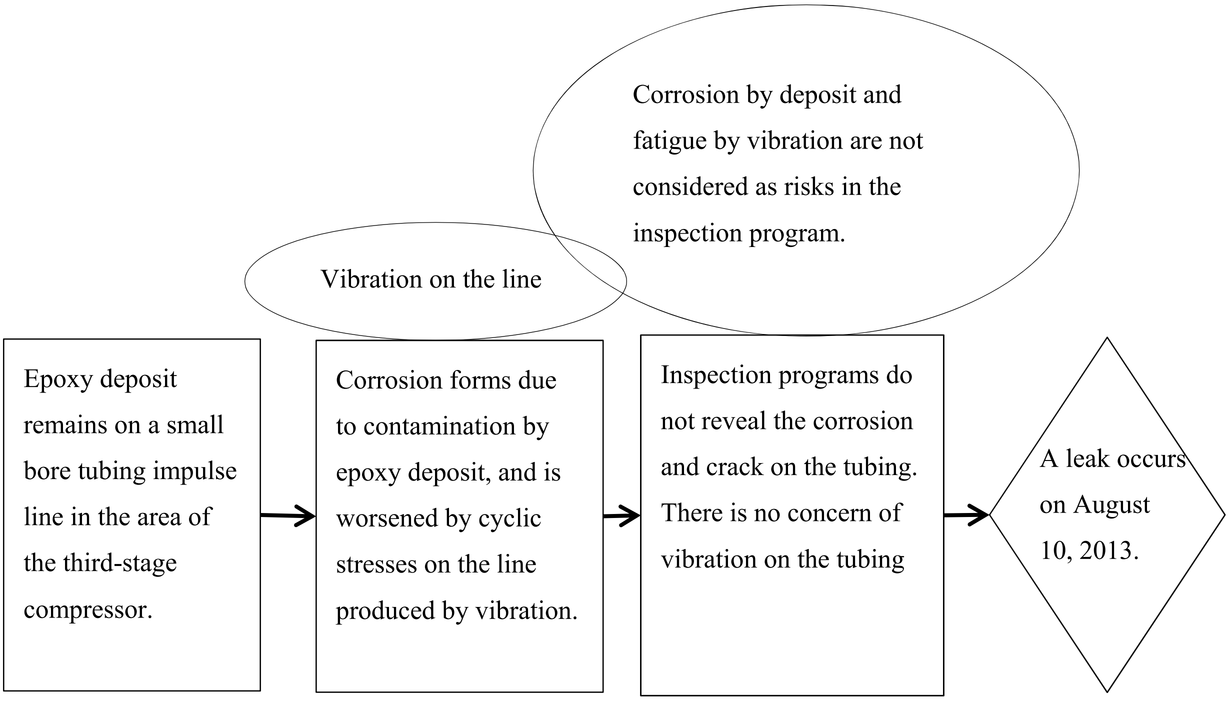


Figure 6.14 Event and casual factors chart of 03534

03553

The description and event and causal factors charting of the incident is based on the report from Step Change in Safety (2014a). Since the exact platform is not presented in the source, the incident is recorded as its alert ID, 03553.

On March 26, 2014, a gas leak occurred with a loud bang from a ball valve installed in a gas compression module on a platform in the UKCS. As the leak was due to extensive chloride-induced stress corrosion on trunnion cap screws on the valve, the initiating event is A6, external corrosion. Visual inspection in November 2013 was performed on the valve, and no faults were reported. Thus, it is assumed that corrosion developed very rapidly since then. This is possibly because there was a deluge event, as suggested by the context in the source that the valve was located within deluge coverage, increasing exposure to a chloride. High temperature also affected the development of corrosion.

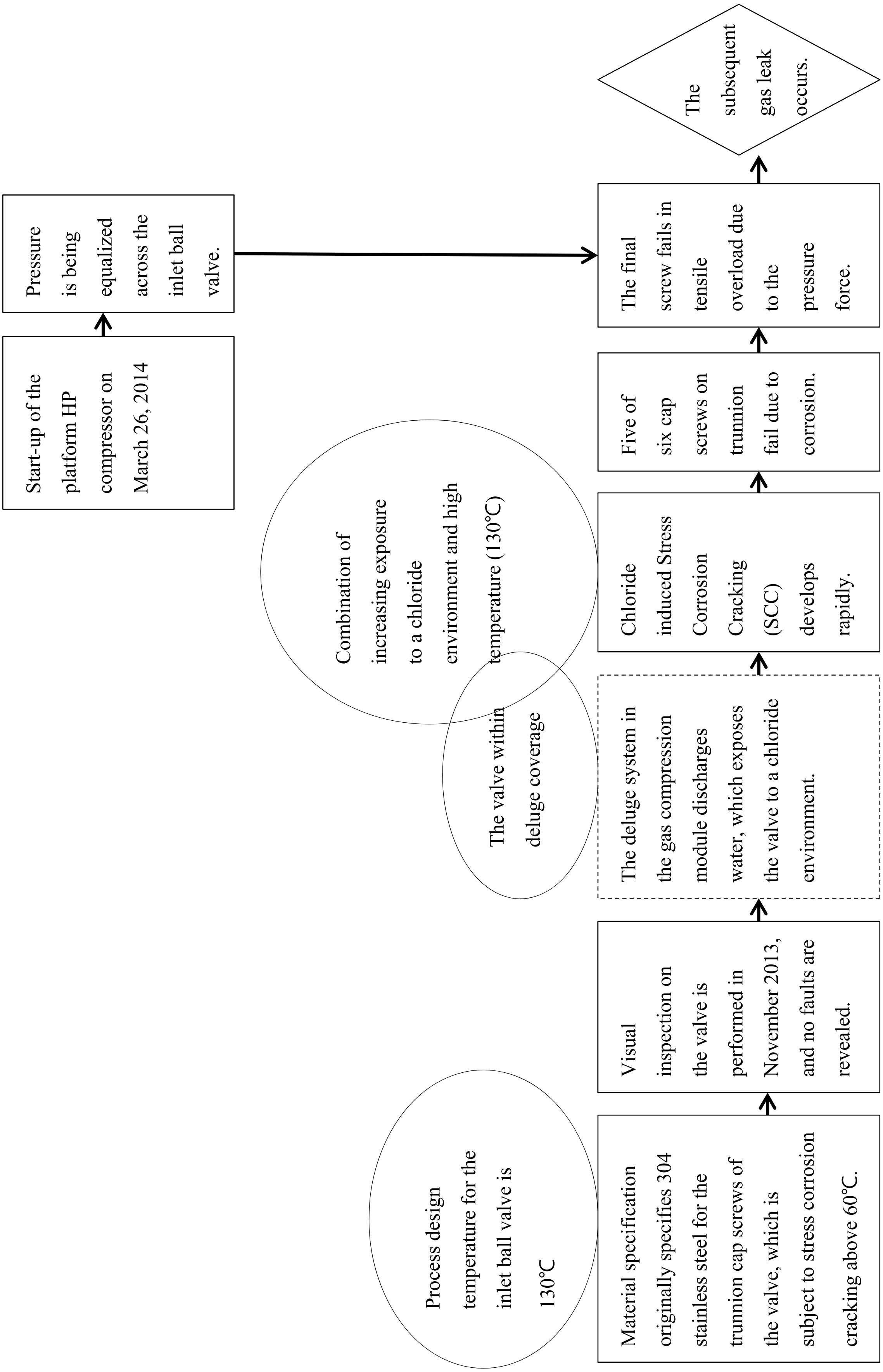


Figure 6.15 Events and causal factors chart of 03553

6B 5165, Platform A

The description and event and causal factors charting of the incident is based on the report from BSEE (2009).

On December 7, 2008, between the hours of 0400 and 0700, an oil leak occurred as result of a ½”-diameter hole in the #4 production shipping pump can, on Platform A, located in area 6B, block 5165, in the Pacific Ocean off California, U.S. As the hole was caused by the accelerated external corrosion, it is recorded as a leak due to A6, external corrosion. It is estimated that between 20 and 30 barrels were released into the Pacific Ocean in the Santa Barbara Channel. Eleven vessels responded to the spill, and an estimated 20 barrels of crude oil/emulsion were recovered.

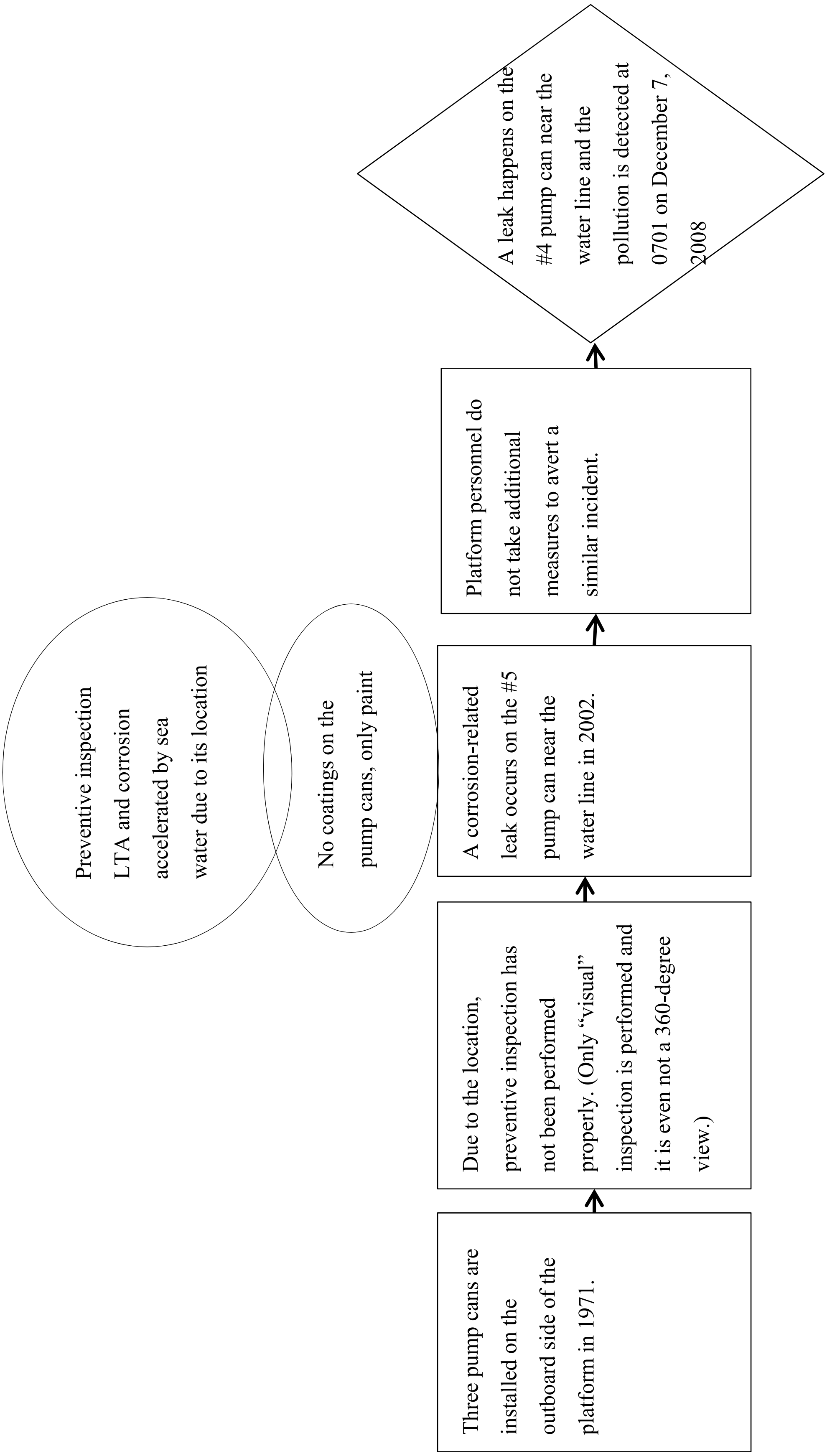


Figure 6.16 Events and causal factors chart of 6B 5165, Platform A

6.7 Erosion (A7)

Oseberg A

The description and event and causal factors charting of the incident is based on the report from the PSA (2014a).

An HC leak occurred on the Oseberg A platform in the North Sea located 140 km northwest of Bergen on June 17, 2013. Unstable flow from Well B-45 which was producing at the moment caused HP in the test manifold. Gas injection into Well B-41 which was connected with Well B-45 on the same branch from the test and production manifold, increased the pressure further. Thus, a control room operator opened the blowdown line from the test manifold in order to blow off the pressure. Sand erosion was being developed in the blowdown line due to the unfavorable design of the line since sand production started around 2000. The blowdown pressure along with already developed erosion created a hole in the line. Therefore, the leak is classified as initiating event type A7 erosion. No one was injured but 85kg of gas and less than 15 l of oil were released during the incident.

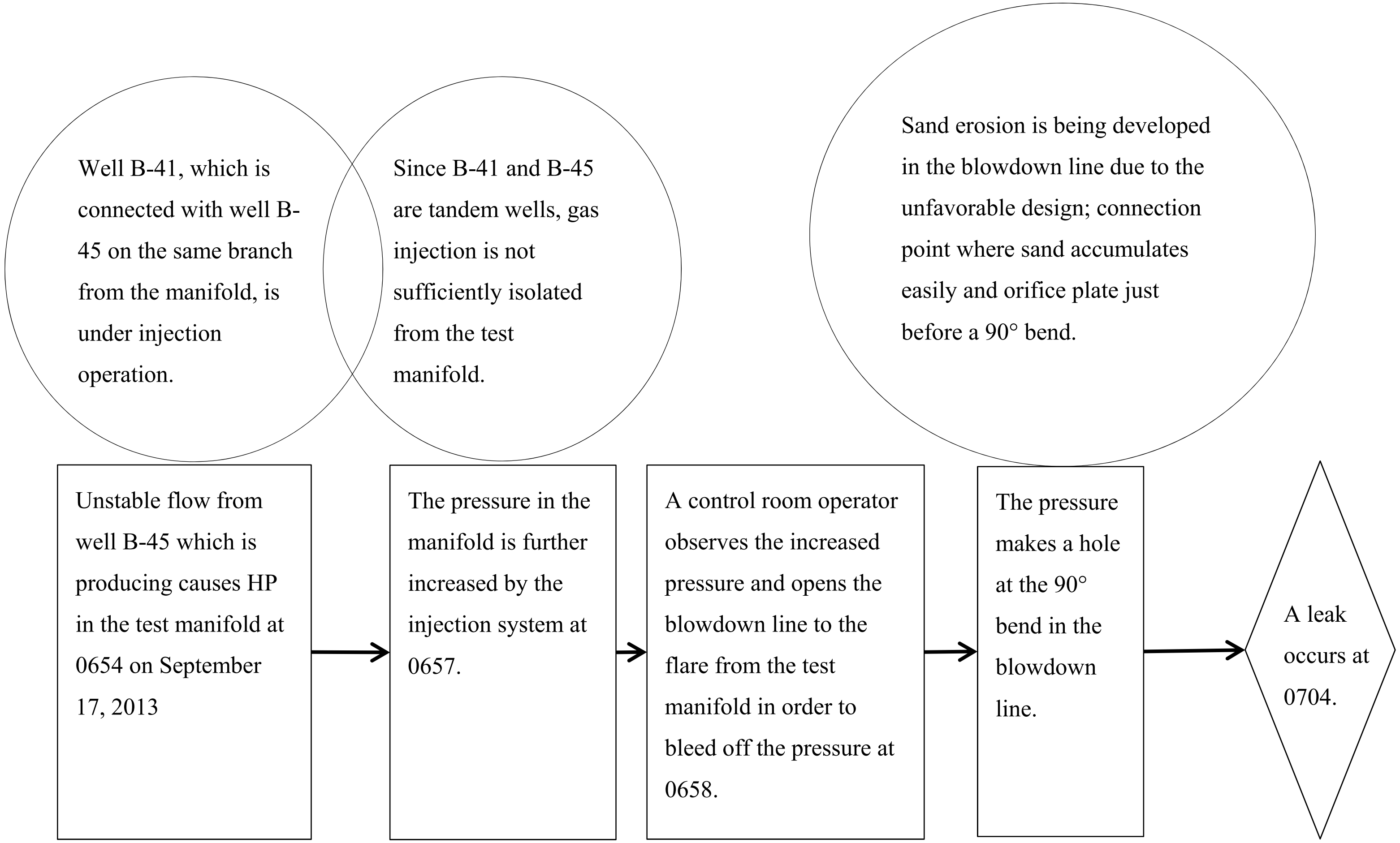


Figure 6.17 Events and causal factors chart of Oseberg A

South Pass 67, Platform A

The description and event and causal factors charting of the incident is based on the report from the BSEE (2005). Due to the lack of information in the source, the description and events and causal factors chart are limited in this incident.

An operator on Platform C observed a sheen coming from Platform A in South Pass block 67, located in the Gulf of Mexico, USA on May 6, 2005. It is believed that the leak started from the fluid transfer pump because the deck under the pump was severely rusted and pitted. The initiating event was A7 erosion of the pump housing due to excessive sand production. The oil released into the sea is estimated at 1.67 barrels and the slick measured 6,160 yards in length and by 60 yards in width.

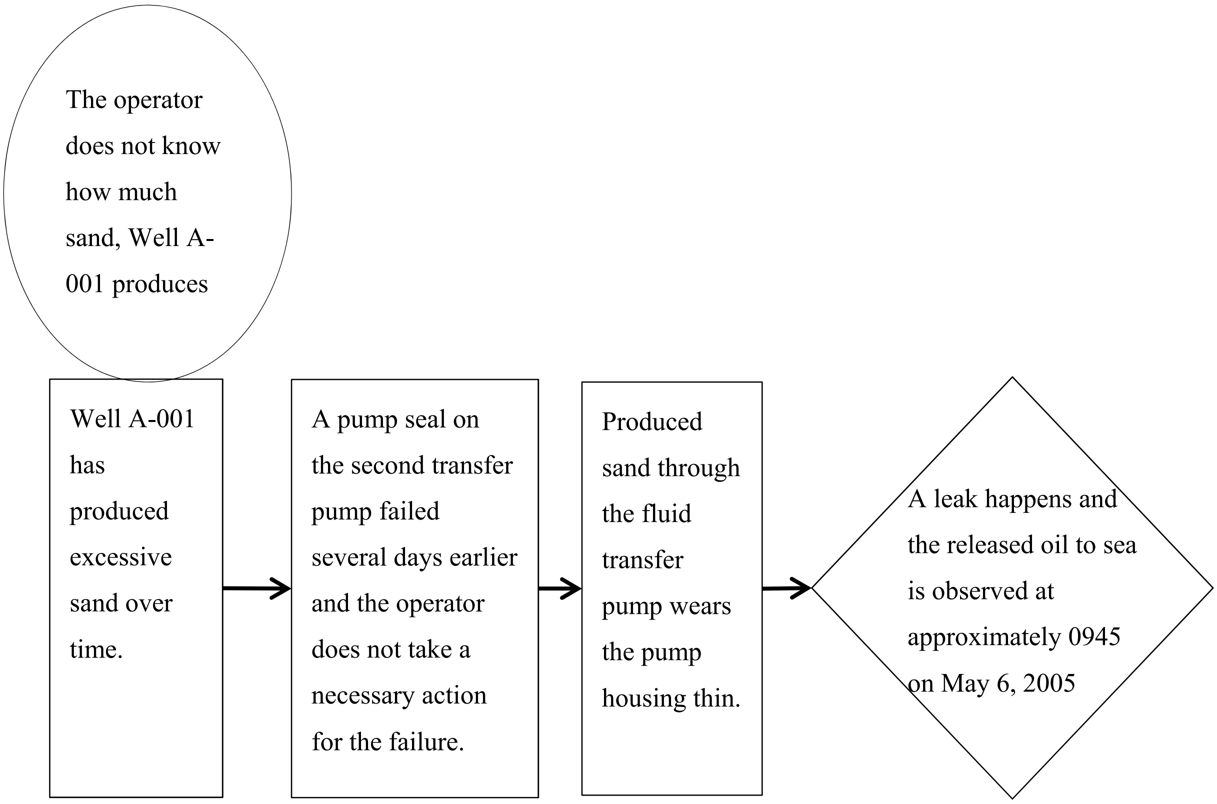


Figure 6.18 Events and causal factors chart of South Pass 67, Platform A

Unnamed 3

The description and event and causal factors charting of the incident is based on the report from the Norwegian Oil and Gas Association (2014e). Since the exact platform and date of the incident is not presented in the source, the incident is recorded as Unnamed 3. Detailed explanation is provided only for the causes.

A gas and oil leak occurred at a 45-degree bend in a pressure relief line on a platform in the NCS in 2014. The pressure relief line had been replaced twice due to erosion, but adequate cause analysis and measures were not implemented. Therefore, an erosion-caused leak with a 0.12 kg/s initial leak rate and 30-minutes duration happened again in 2014. The initiating type is A7, erosion.

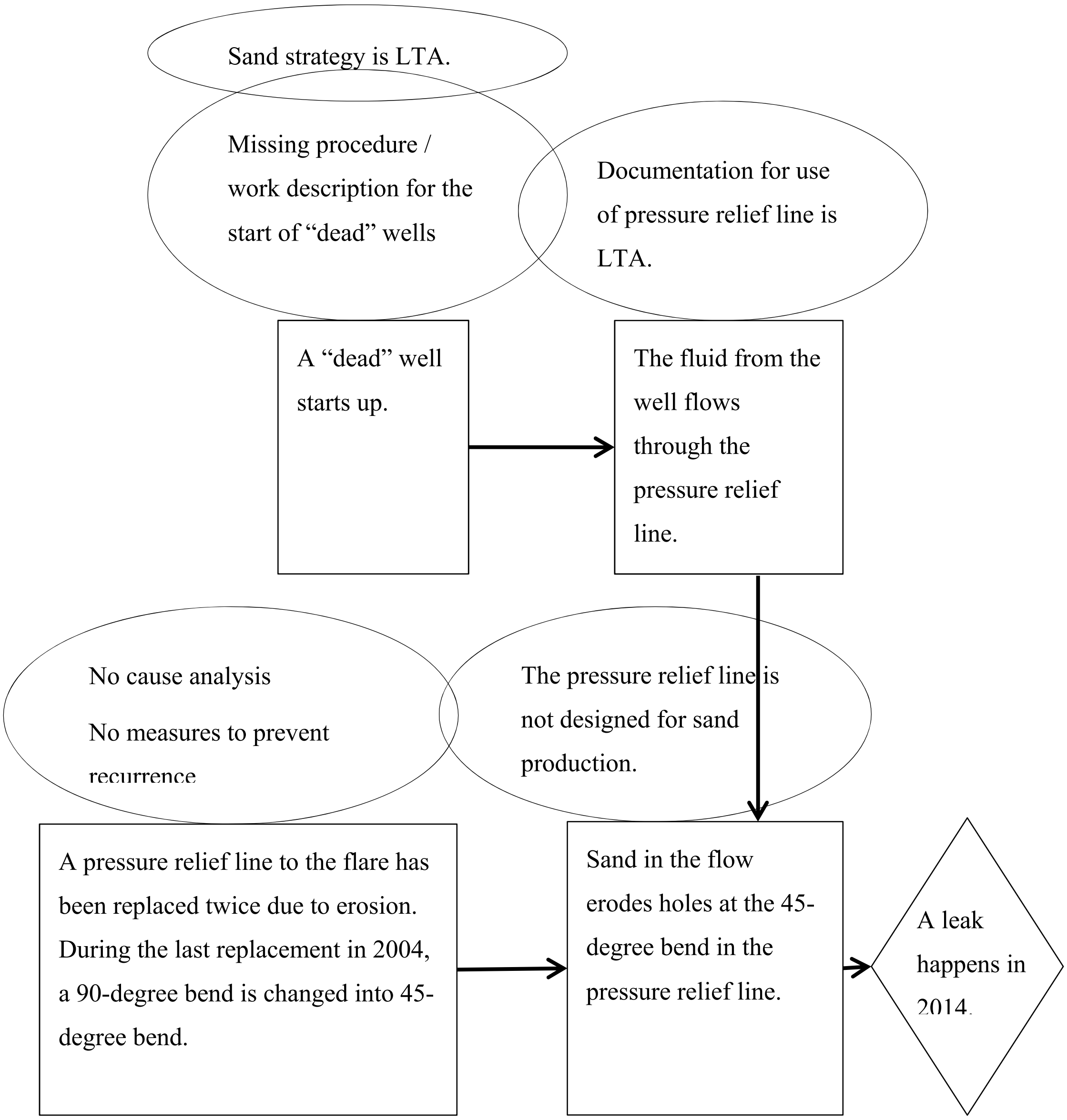


Figure 6.19 Events and causal factors chart of Unnamed 3

6.8 Other causes (A8)

Unnamed 4

The description and event and causal factors charting of the incident is based on the report from the Norwegian Oil and Gas Association (2014b). Since the exact platform and date of the incident is not presented in the source, the incident is recorded as Unnamed 4. Detailed explanation of only the causes is provided.

An oil leak at a rate of approximately 0.16kg/s occurred at the mechanical seal on a mixing pump B on a platform on the NCS in 2013. This was because of the failure of the sealing due to increased frictional heat. Sealing degradation is usually classified into the initiating event A1, but this was recorded as initiating event type A8, other cause due to special circumstances associated with human error. Details about this can be found in the chart. The total amount of released oil was 100kg, and pollution event did not occur.

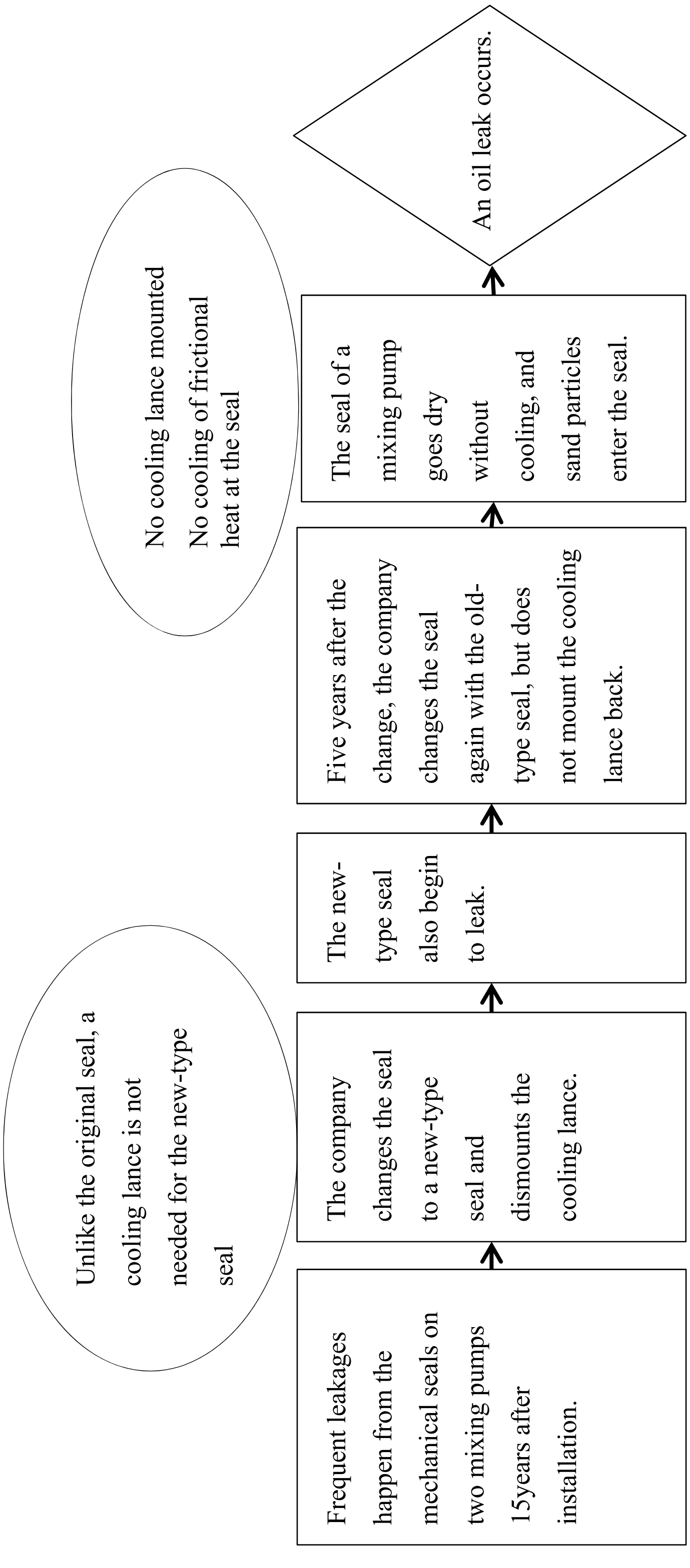


Figure 6.20 Events and causal factors chart of Unnamed 4

6.9 Design related failure (E1)

03486

The description and event and causal factors charting of the incident is based on the report from Step Change in Safety (2014e). Since the exact platform is not presented in the source, the incident is recorded as its alert ID, 03486.

At approximately 0900 hours on May 22, 2013, there was an intermittent trace smell of gas in and around the location of the molecular sieves, but gas was not detected until 1410 hours because a strong wind made detection difficult. At 1410, an operator detected visible gas vapor from the flange joint of a control valve on a HP gas system. Investigation revealed why the flange joint had failed: Thermal expansion together with fixed supports on the control valve resulted in high compression and bending across the leaked flange. The high compression and bending moment made the effective bolting loads decrease and allowed gas to escape. Therefore, the initiating event is E1 design related failure, because fixed supports on equipment with the large variation of pressure and temperature were absolutely the wrong design.

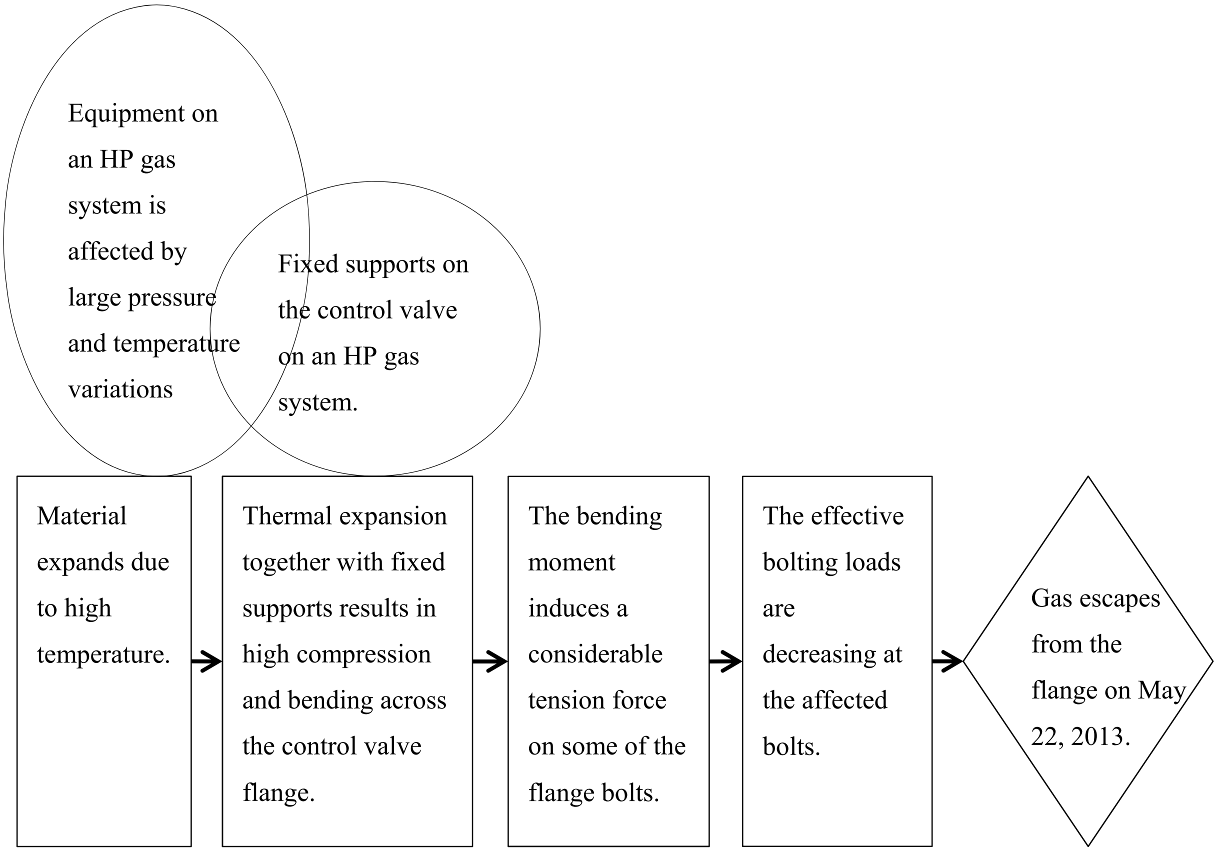


Figure 6.21 Events and causal factors chart of 03486

Unnamed 5

The description and event and causal factors charting of the incident is based on the report from Norwegian Oil and Gas Association (2014d). Since the exact platform and date of the incident is not presented in the source, the incident is recorded as Unnamed 5. Detailed explanation of only the causes is provided.

A gas leak occurred in connection with the function test of a blowdown valve from a measurement package on a platform in the NCS in 2014. The incident was due to an unclosed seal between a flange and a blind in the measurement package; the seal was not tightened because the width of the groove for the seal in the blind was too wide. Thus, the initiating event type is classified as E, design failure. As a result, a gas leak of approximately 0.2kg/s lasted for 50 minutes and total emissions were around 600 kg.

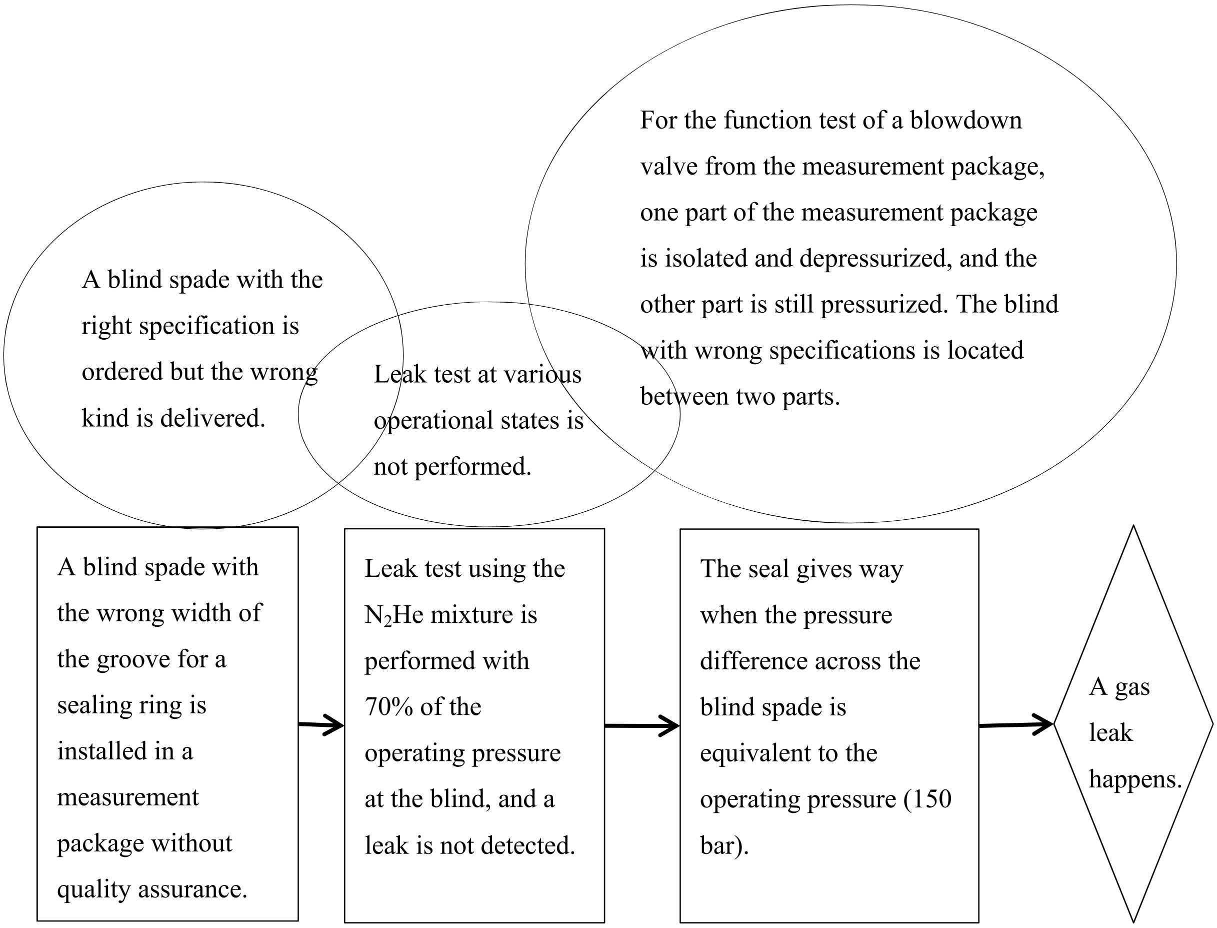


Figure 6.22 Events and causal factors chart of Unnamed 5

Visund

The description and event and causal factors charting of the incident is based on the report from the PSA (2006).

A substantial gas leak from a hole in a flare pipe on platform Visund, in the NCS occurred on January 19, 2006. As the direct cause was design flaws of the outlet arrangement from a Knock-Out (KO) drum, the initiating event is E, design related failure. No one was injured, but the hole was massive and the leak rate was 900kg/s; accordingly, the potential consequences were severe. How the design flaws led to a massive hole in the flare pipe is illustrated in the events and causal factors charting.

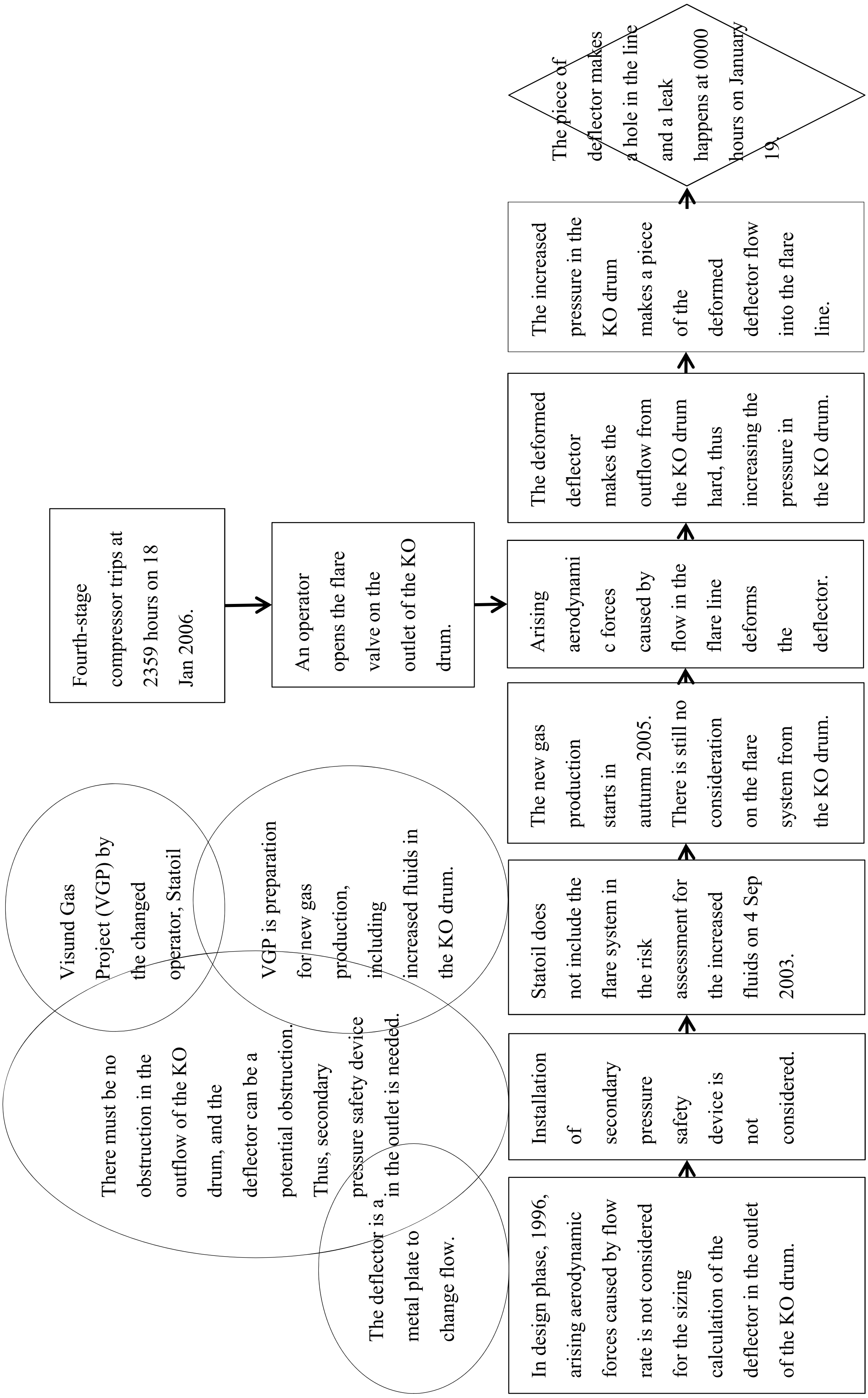


Figure 6.23 Events and causal factors chart of Visund

West Cameron 198, Platform A

The description and event and causal factors charting of the incident is based on the report from the BSEE (1996).

On December 15, 1995, the platform operators observed a spill from the sump tank on Platform A, located in West Cameron block 198 in the Gulf of Mexico, off the Louisiana Coast, USA. All the valves on lines to the sump tank were in the closed position, but the ball and body of a valve on a drain line from the HP separator to the sump tank were cut out and the valve was not completely closed at the time of incident. Thus, hydrocarbons flowed into the sump tank, and were released through the thief hatch and water leg of the tank without the actuation of the Level Safety High (LSH) of the tank due to its ineffective configuration. Both the leaking valve and the pump's ineffective LSH configuration are the causes of the incident, but the author considers this incident as the initiating type E1, design-related failure, since the reason why the valve was leaking was not ascertained by BSEE (1996). The spill volume was estimated at 740 barrels.

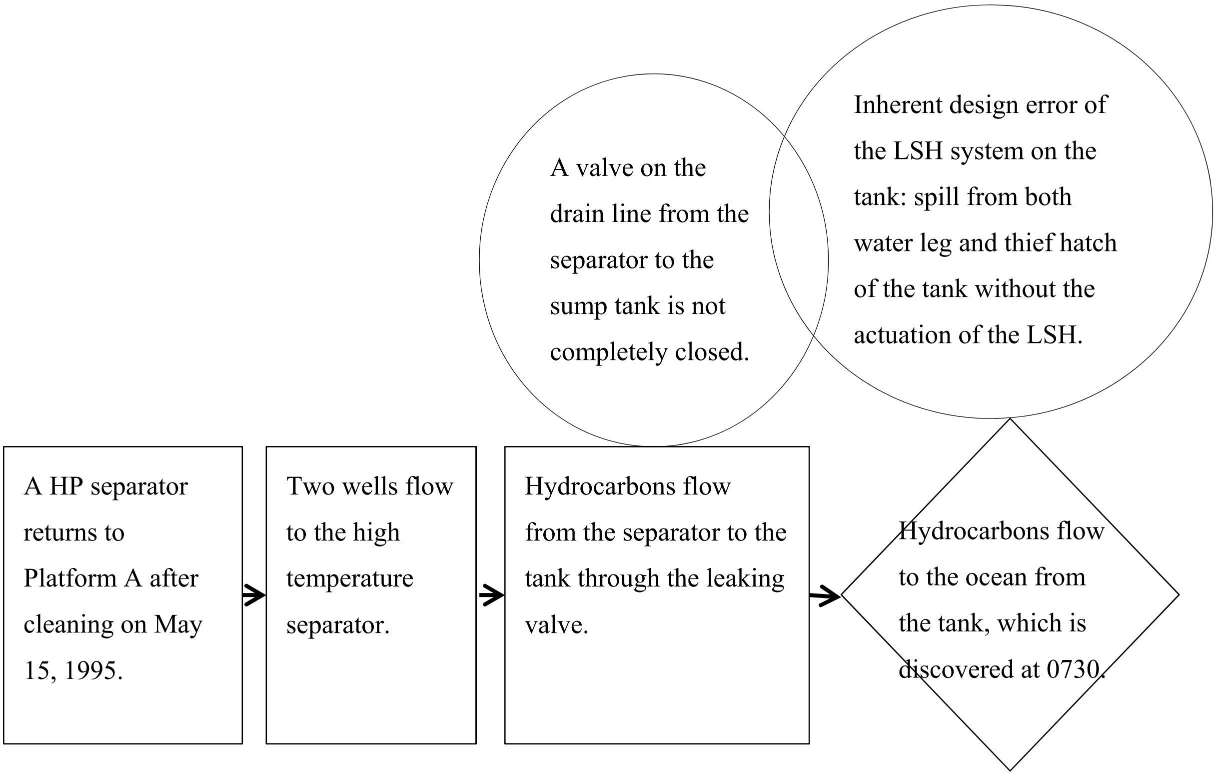


Figure 6.24 Events and causal factors chart of West Cameron198, Platform A

Åsgard B

The description and event and causal factors charting of the incident is based on the work of Endresen, Hinderaker, and Solheim (2006).

An oil leak in one of the pipe oils in Heat Exchanger A on Åsgard B operated by Statoil, in the NCS occurred on October 12, 2005. The direct cause was deficiencies in the design of the heat exchanger; hence, the initiating event is E, design related failure. No one was injured, but the released oil ignited and led to a fire. It had a potential dangerousness because the flame detector did not detect the fire initially. The actual consequence was minor material damage.

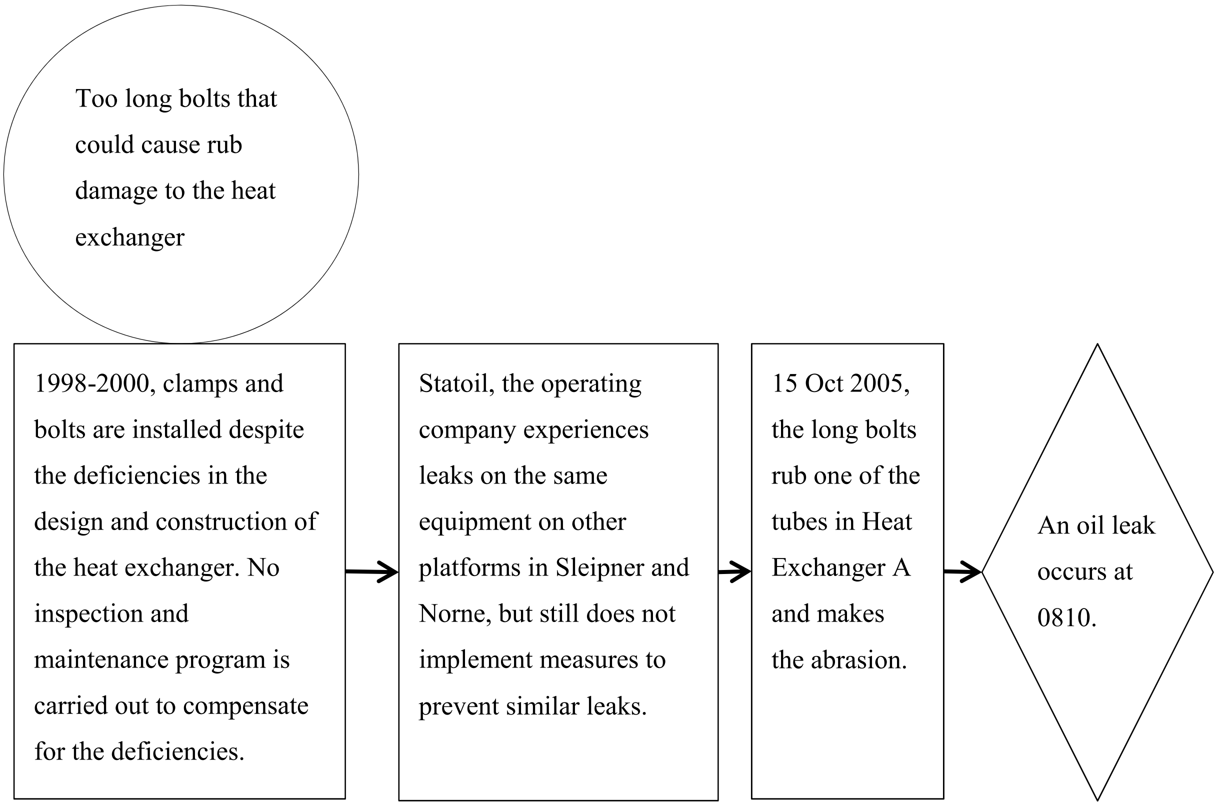


Figure 6.25 Events and causal factors chart of Åsgard B

7 Modeling

Based on the investigation of non-operational leaks, modeling for A- and E- type leaks is presented in this chapter (for initiating event type, see Table 2.1). D- and F- type leaks (which are leaks due to process disturbance and external events, respectively) are omitted, because the occurrence of those leaks has been decreasing of late; hence, their impact is negligible: According to Vinnem and Røed (Subitted for publication), process disturbance and external impact caused only one leak each on the NCS in the period 2008-2010. In 2011-2013, there was no single leak associated with process disturbance or external impact.

As the Risk OMT model presents generic risk influence diagrams for leak caused by human error, the model to be presented in this chapter also consists of generic risk influence diagrams, a step further from BORA-Release. In this process, risk influence diagrams are developed using BBNs and event trees are developed to show the leak scenarios from an initiating event to multiple end events (here, simply "leak" and "no leak" are considered). Leak scenarios are identified only for leaks due to technical degradation (A-type).

7.1 Leaks due to technical degradation (A-type initiating event)

Leak scenarios with A-type leaks are simpler than the leak scenario presented in the Risk OMT model (Figure 5.6). This is because technical degradation events have little correlation with each other; so, an event tree describing relevant leak scenarios is established for each initiating event. On the other hand, initiating events B1-B4 are modeled together in an event tree of the Risk OMT model because they are all results of the work operation "work on isolated depressurized equipment."

Figure 7.1 shows a generic event tree for technical degradation leaks. The leak scenarios starts from an initiating event, and may involve another event to trigger a leak or/and failure to detect the technical degradation. Once another event occurs when an initiating event has already happened, hydrocarbons are released. Even though there is no additional event after an initiating event, hydrocarbons are also released if the degradation is not detected and develops further until failure level. Each pivotal event in Figure 7.1 is explained below.

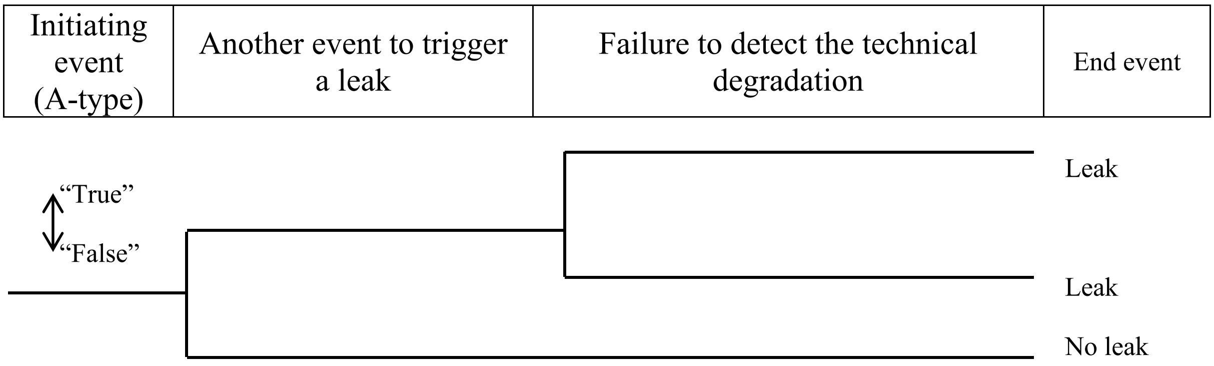


Figure 7.1 Generic event tree describing leak scenarios associated with technical degradation

- Initiating event: A-type initiating events are associated with technical degradation such as corrosion and erosion. It can be discussed how severe degradation must be in order to be considered as an initiating event. The state that technical degradation develops significantly but that the degradation alone does not lead to a leak is regarded as an initiating event. RIFs for this pivotal event are divided into common RIFs for all technical degradation and RIFs only for the specific degradation.
- Another event: Another event is not relevant to technical degradation but trigger a leak at the state where an initiating event has already happened. These events can be pressure increase, unintended valve opening, and so on. In particular, pressure increase, the most common event to cause a leak, can occur due to either an unintended event, such as a trip of some equipment, or an intended action, such as a start-up process from shut-in condition. This pivotal event plays a decisive role in provoking a leak at an early stage of degradation development, as seven of 20 investigated A-type leak incidents include the event. However, the RIFs for this pivotal event are beyond the range of this thesis since it is not relevant to technical degradation, and not examined further.
- Failure to detect technical degradation: As the last barrier to prevent a leak is detecting technical degradation (here, detection of technical degradation includes detection and corrective action to prevent a leak.), the last pivotal event becomes failure to detect technical degradation. The difference from an initiating event is that technical degradation at this state further develops to such an extent that it causes a

leak without any other event. Therefore, failure to detect technical degradation means a leak occurring immediately.

It is important to note the characteristics of the initiating event and failure to detect technical degradation. Although they are pivotal "events" in Figure 7.1, they are not the events that happen at a certain time. Degradations develop over time, and there are several opportunities to detect degradations over time. Thus, the author uses the extent of degradation to describe and distinguish between two events. Figure 7.2 illustrates this: The grey line represents technical degradation over time, and the significant and failure levels are the extents of degradation for initiating events and failure of detection, respectively. However, there is no clear demarcation between two events; therefore, there is a risk of double counting when using this model quantitatively. Nevertheless, because some technical degradation is detected after deterioration over the allowable level (which could be considered that the initiating event happened but the failure of detection did not happened yet), there is a need for having two separate events.

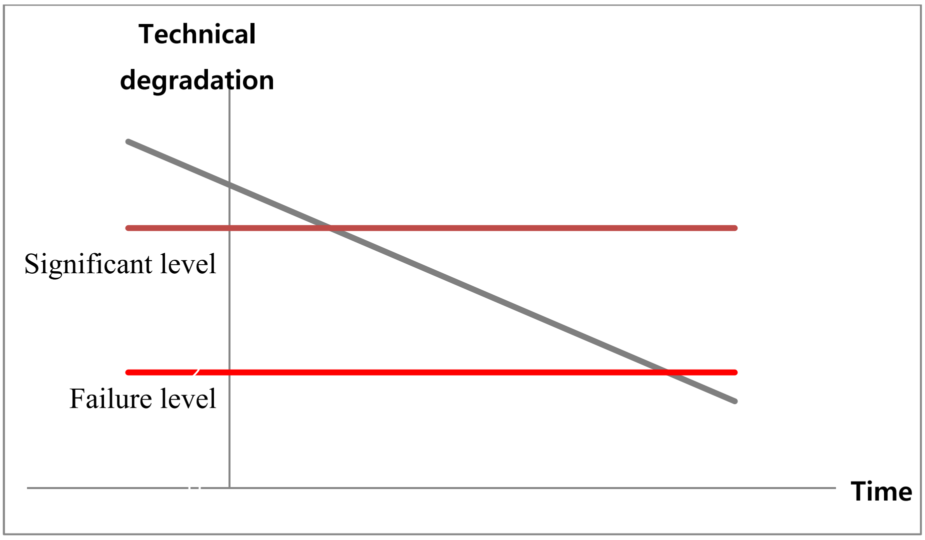


Figure 7.2 Technical degradation over time with significant and failure levels

Establishing risk influence diagrams for initiating events is the next step (RIFs for "another event" and "failure to detect" are not covered in this thesis). The identified RIFs are based on the investigation of A-type leaks (20 leaks in total) in Chapter 6 and other sources for initiating events A1-A4 due to the lacking number of investigated leak incidents. Appendix A briefly illustrates which incidents are relevant to which RIFs, and the description of all the identified RIFs can be found in Appendix B.

The risk influence diagram for A1 degradation of valve sealing is illustrated in Figure 7.3.

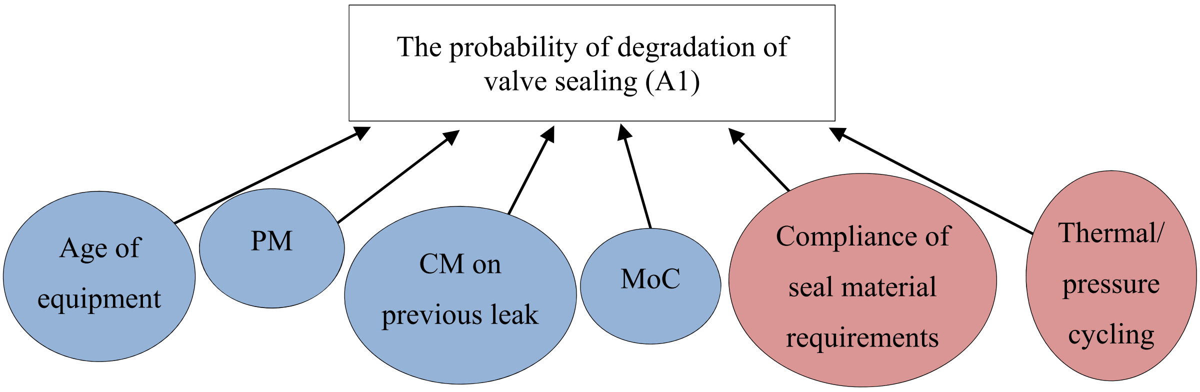


Figure 7.3 Risk influence diagram for degradation of valve sealing (A1)

RIFs are divided into common RIFs for all technical degradations (blue) and RIFs only for the degradation of valve sealing (red). RIFs for all technical degradations are general factors influencing all technical degradation from A1 to A8. Age of equipment, PM, CM on previous leaks, and Management of Change (MoC) are identified for this category. Age of equipment is a factor reflecting the nature of degradation, with all technical degradations inherently progressing over time. However, in the case of age of equipment not being a direct cause of a leak, investigation reports tend not to provide information about age. In fact, only four incident reports mentioned oldness of equipment as a direct cause of the leaks. On the other hand, PM is the most frequent RIF that is noted to cause technical degradation. This is because PM not only is highly involved in technical degradation, but also offers comprehensive meaning, including several activities or influencing factors. Thus, PM is divided further, making the RIFs on the second level. Figure 7.4 illustrates the risk influence diagram for PM.

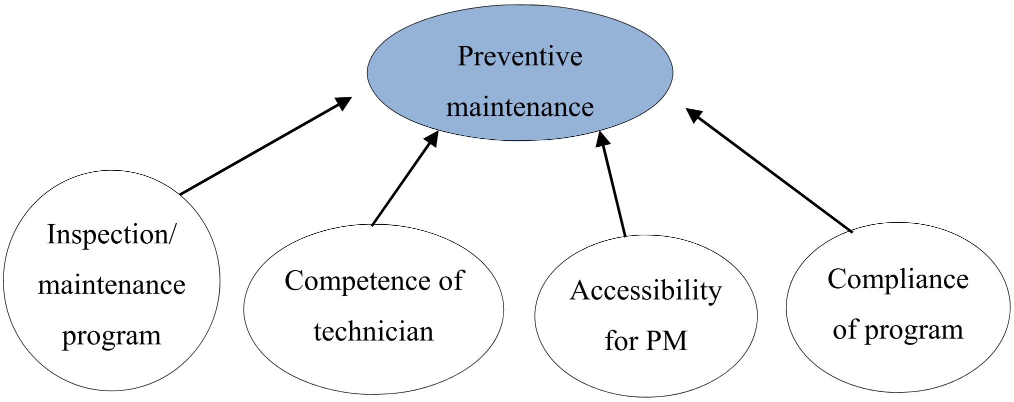


Figure 7.4 Risk influence diagram for preventive maintenance

The four illustrated second-level RIFs have an effect on technical degradation indirectly, through PM on the first level. For example, inadequate sand strategy of the incident “Unnamed 3” will contribute to a bad score on “Inspection/maintenance program” and the pump can on the outboard side of the platform of the incident “6B 5165, Platform A” will have a low score for “Accessibility for PM.” These bad scores of the second-level RIFs affect PM, and finally technical degradation. CM on previous leaks and MoC, the two remaining common RIFs, depend on CM after previous leaks and the risk assessment (and following measures) regarding process/equipment changes, respectively. Consequently, if there was no previous leak and no change, the scores of the RIFs are regarded as A, best practice.

These common RIFs, except “age of equipment,” reflect the cultural aspect and the general management of the installation, rather than the influence of a single technician or specific equipment. Naturally, the effect of these common RIFs is on all relevant initiating events, thus, they are separated from specific RIFs. The advantages of having common RIFs are: 1) RIFs can be found for a rarely occurring initiating event by applying RIFs identified for other initiating events. 2) It is easier to use this model for leak frequency estimation since the same scoring and calculation for those RIFs are used repeatedly across all technical degradations.

On the other hand, specific RIFs for the degradation of valve sealing can be compliance with seal material requirements and thermal/pressure cycling. Since it is impossible to find specific RIFs through only two incident investigations, the RIFs are also identified through the works of (Ho, 2006; Ho, Edmond, & Peacock, 2002); Kruijer (2010). As manufactures provide specifications for seal material, the most important thing is to comply with the requirements of seal material regarding temperature, pressure, and chemicals. Many studies, including those of (Ho et al., 2002); Kruijer (2010) emphasize the influence of temperature, pressure, and chemicals on seal degradation. Furthermore, even though requirements are met, fatigue by thermal/pressure cycling is risky; Ho (2006) especially highlights the fatigue of elastomeric seals subjected to multiple Rapid Gas Decompression (RGD), which is also known as Explosive Decompression (ED).

The next initiating event is degradation of flange gasket. Figure 7.5 is the risk influence diagram for degradation of flange gasket, and the RIFs are identified through literature review due to the lack of investigated incidents. Gaskets share similar characteristics with valve seals as a sealing device; however, there is less variety in types and materials. Ring gaskets made of metal are mainly considered when determining the factors that influence gasket degradation.

According to Bickford (1997), temperature (especially, heat) is the main cause of gasket degradation, and other working conditions, including gasket compressive stress, internal fluid type, pressure, gasket geometry, and flange rigidity, have similar importance. Therefore, they are considered as a RIF, and to be evaluated together or separately if a single working condition is significant.

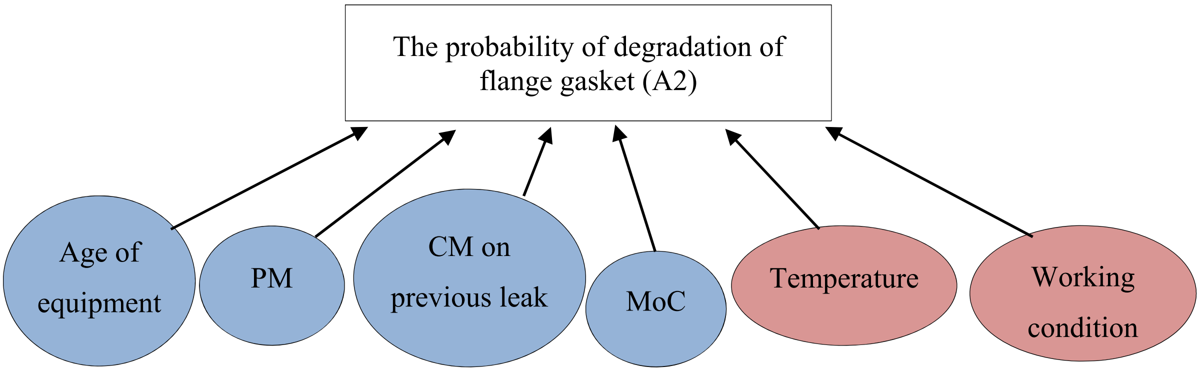


Figure 7.5 Risk influence diagram for degradation of flange gasket (A2)

In case of the loss of bolt tensioning (A3), a literature search was also performed to identify the RIFs. According to Bunai (n.d.), there are five major reasons for bolts to loosen; transverse movement due to vibration, relaxation due to embedment or gasket creep, elastic interaction of multiple bolts in a bolted joint, thermal expansion, and insufficient initial preload. Among them, relaxation, elastic interaction, and insufficient initial preload are relevant to installation and tightening; so a RIF is identified as compliance of installing and tightening requirements. The other RIF is vibration and temperature, which affect the first and the fourth of the mentioned reasons as well as gasket creep and elastic interaction. Figure 7.6 gives an overview of this.

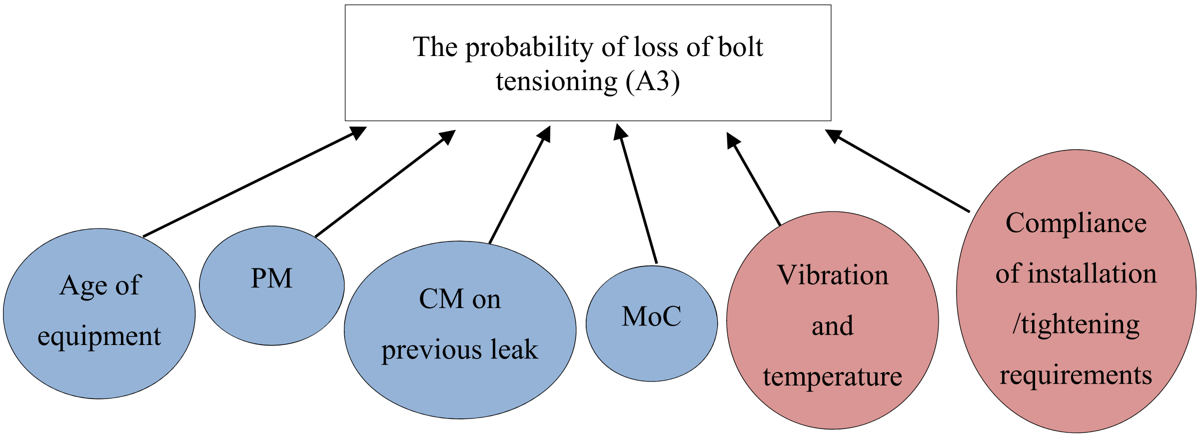


Figure 7.6 Risk influence diagram for degradation of loss of bolt tensioning (A3)

The RIFs on fatigue can be found in Figure 7.7: fatigue limit of material and cyclic loading. Since fatigue is a damage process of materials caused by cycling loading (Lee, Pan, Hathaway, & Barkey, 2005), the influencing factors become a property of materials to represent the limit amount and number of cyclic stress (fatigue limit of materials), and the amount and frequency of applied load in the working condition in question (cyclic loading). Corrosion, temperature, overload, and metallurgical structure can be additional factors that accelerate fatigue (Udomphol, 2007); however, they are not included in the risk influence diagram because effective PM is more critical after a small crack is initiated.

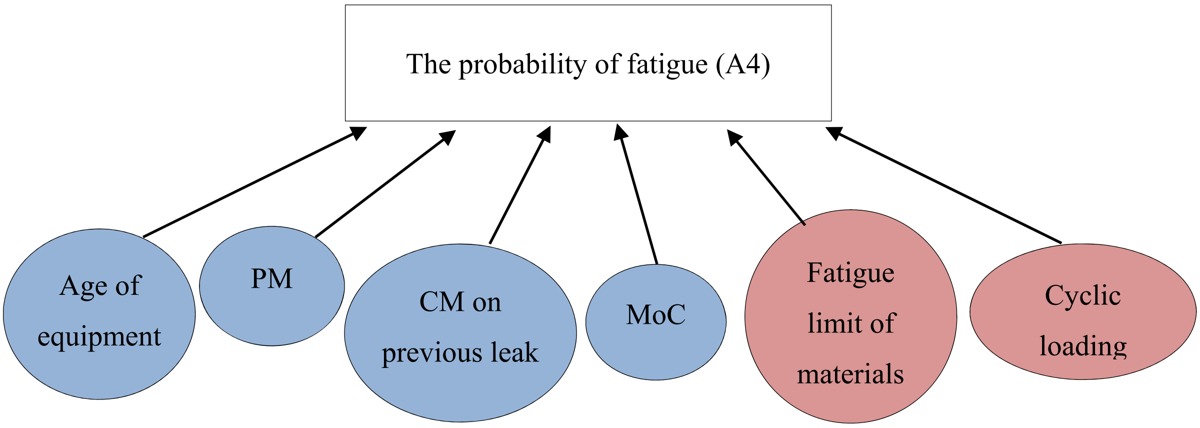


Figure 7.7 Risk influence diagram for fatigue (A4)

As for internal corrosion, the main influencing factor is corrosive fluid inside pipework and a temperature high enough for corrosion. For instance, chloride in produced water inside a valve and ambient at high temperature corroded the valve steel and made a leak in the Ula P incident. Another factor is steel type. In the Hermosa incident, the pipe steel was selected on condition that no water would be produced, and this precondition not being followed was the main cause of the leak. Of course, this is a fault of PM, but it is also true that a steel type with constraint condition is risky when any process change occurs or PM is not performed well. The risk influence diagram for internal corrosion, including these RIFs as well as common RIFs, can be found in Figure 7.8.

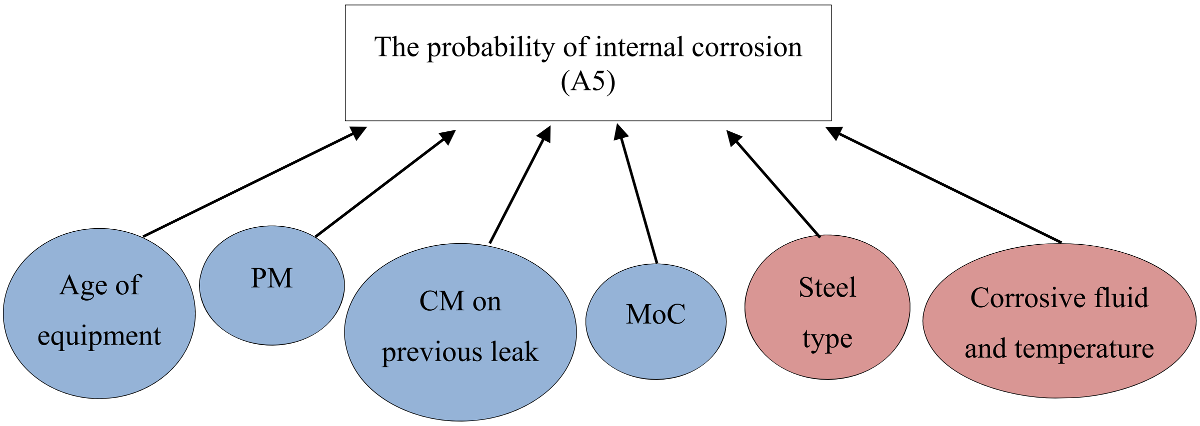


Figure 7.8 Risk influence diagram for internal corrosion (A5)

The next technical degradation is external corrosion with three particular RIFs. Steel type is chosen for a similar reason as the RIF, steel type, for internal corrosion. In contrast, the other RIFs explain external issues. Coating is essential for protecting pipework when the "optimum" environment for corrosion is expected. Since Corrosion Under Insulation (CUI) needs extra care, insulation is also included and is relevant to PM (access for PM is virtually impossible). Environment covers corrosive substance, temperature, residual substance, and construction details. That epoxy deposit remained on bore tubing in the 03534 incident can be an example of residual substance. In addition, the 03527 incident, where a leak occurred at a low point of the pipe due to accumulated water there shows how construction details can increase the likelihood of external corrosion. Figure 7.9 illustrates this.

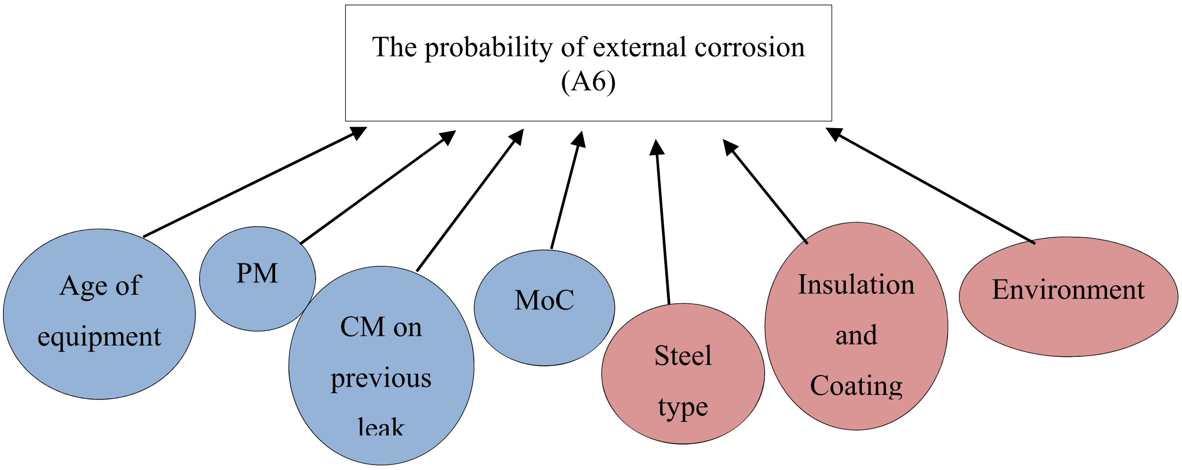


Figure 7.9 Risk influence diagram for external corrosion (A6)

In case of erosion, sand is the primary cause. Pipework or a pump housing was eroded by sand in all three investigated incidents (Oseberg A, South Pass 67 A, and Unnamed 3). Moreover, because sand can accumulate at times of low flow, it becomes concentrated in particular parts of the production pipework (usually elbows) and increases erosion rates (Barton, 2003). Unfortunate design aggravates this. For instance, the pressure blowdown line in case of the Oseberg A incident had an unfortunate connection to test manifold; so, sand easily accumulated at the connection. There was also an orifice plate just before a 90° bend, which made sand flow with high velocity before it hit the bend. Two features of the design were very unfavorable with regard to sand production and, finally, hydrocarbons were released through a hole at the 90° bend. Therefore, design and location are to be considered together as a RIF, as shown in Figure 7.10.

The last category of technical degradation, other causes, is not modeled with a risk influence diagram, because incidents in this category are not specified. However, this type of incidents is also caused by technical degradation, so that the common RIFs can be used.

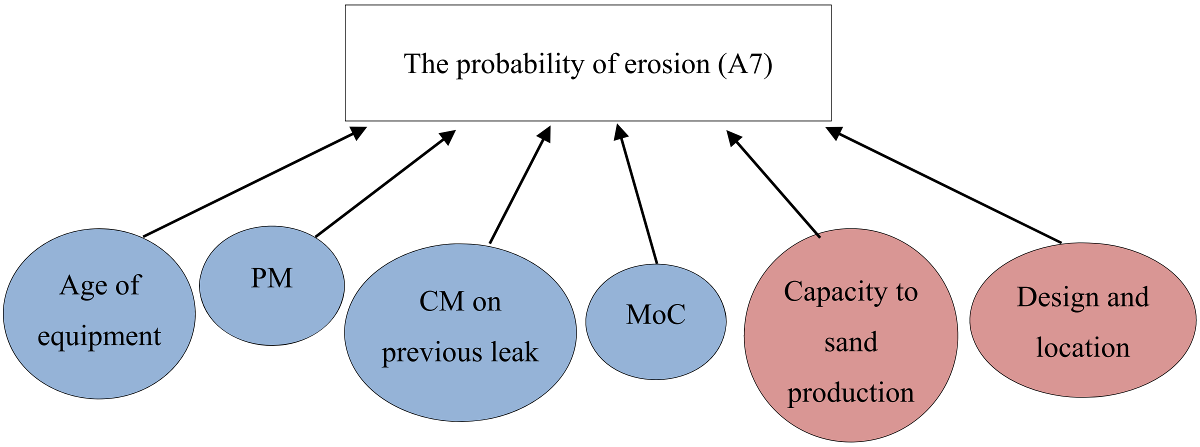


Figure 7.10 Risk influence diagram for erosion (A7)

7.2 Leaks due to inherent design errors (E-type initiating event)

To determine the RIFs on inherent design errors, what causes design errors needs to be examined in a similar way to the RIF identification for technical degradation. However, most investigation reports do not provide why design errors happened even though they explain the causes of technical degradation. This is because the causes of design errors are hard to reveal since design errors were made some time ago (in the designing phase), unlike technical degradation which develops during operation. Besides, the causes of technical degradation, such as fatigue, corrosion, and erosion, are well- known, but this is not the case for design error. Therefore, a different approach is needed to deal with inherent design errors.

The approach is to use literature on design error causation and classification, rather than accident investigation reports. The causes of design errors are thoroughly examined in literature, as this is impossible for an investigation team to figure out by looking into only one accident. However, the causes found in literature also need reconsideration because the causes should be modified into RIFs from the point of view of operating companies that need to use this model. The risk influence diagram presented in Figure 7.11 is made in this sense. However, it does not mean that design error causation and prevention in design phase are not important; rather, design error correction in the design phase can be a higher priority but is not covered in this model. In which phase (design phase or operation phase) design error should be treated is further discussed in Chapter 8.5.

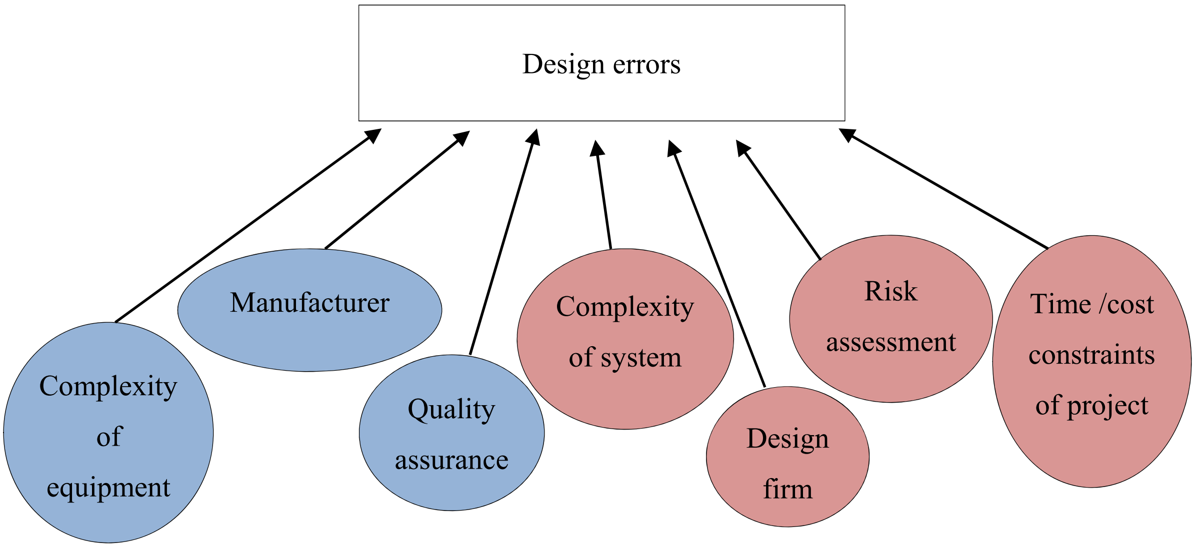


Figure 7.11 Risk influence diagram for design errors

The identified RIFs in Figure 7.11 are based on design error classification in the work of Lopez, Love, Edwards, and Davis (2010). First, the RIFs are divided into two categories: equipment level (blue) and system level (red). This is because an HC leak can occur due to either a fault of a piece of equipment or mismatch of equipment to the overall system.

In the equipment level, the complexity of equipment is a factor representing how complex the equipment is, and high complexity inherently increases the likelihood of design errors. The RIF, manufacturer, represents how reliable the manufacturer is, and involves the experience, training program, and so on. Lopez et al. (2010) claim that design errors are due to designers' loss of biorhythm and adverse behavior at the personal level; however, an operating company cannot evaluate those factors for quite a long time after equipment is designed. Instead, an operating company evaluates the reliability of the manufacturer with regard to its experience, history of design errors, training program and standard. This approach with a focus on an organization, rather than on a single person, is also in accordance with the perception that designers cannot guarantee the results of the service; instead, the liability for errors and omissions is determined by their community (Lopez et al., 2010). The last RIF in the equipment level, quality assurance, can be evaluated by function tests before and after installation.

In the system level, two RIFs—the complexity of system and design firm—are identified with a similar reason as the complexity of equipment and manufacturer in the equipment level. Risk assessment also has a similar function as quality assurance in the equipment level. However, since system is a more complicated than a piece of equipment, a thorough review is needed on the risk assessment document when evaluating the RIF. Finally, the time/cost constrains of a project is added. According to Josephson and Hammarlund (1999), the causes of defects in design can be classified into knowledge, information, motivation, stress, and risk, and the proportion of defects due to motivation or stress in the investigated seven projects in their study was 37%. Since motivation and stress mainly come from time and cost constraints, they are modeled as a RIF.

An event tree for event sequences from design errors to a leak is not established, unlike for technical degradation as shown in Figure 7.1. This is because the quality assurance and risk assessment of RIFs on design errors already involve detection of design errors. Furthermore, the logic that a leak occurs a certain time after an initiating event occurred without detection is not valid for design errors, because the likelihood of a leak due to design errors is not increasing with time. Therefore, the risk influence diagram is only considered in the present model, and more research is needed to determine event sequences form design errors to a leak in a general sense.

8 Discussion

This chapter discusses the usefulness and limitations of the model developed in this project. Also, the alternatives that can be used for the same purpose of this model are suggested, and compared with this model with regard to the advantages and disadvantages.

8.1 Validity of the model

The validity of the developed model is the most critical concern. The discussion on validity can be divided into the reliability of the data used in the model, the usefulness of the result, and the ease of using the model.

First, the data sources used in the model are mainly leak incident investigation reports to identify the leak scenarios and the RIFs. The reports were provided by either operating companies or safety authorities, and the provided information in accident investigation reports is quite different, according to the interest of the providing organizations (PSA, 2011). Especially, operating companies might have omitted some information to safeguard their interests. Furthermore, according to PSA (2011), important information can be omitted unintentionally due to the experience of an investigation team, severity of an incident, accident model, and the timing of the investigation. However, to compensate for this, the relevant literature review was performed; hence, a significant error in RIF identification in the developed model is not expected.

The discussion on the value of the result can start from the approach of the developed model. The approach was quite distinct from the approach of conventional QRA studies to non-operational HC leaks in that the developed model assists in estimating “platform-specific” leak frequencies. This is going to be fully elaborated in Chapter 8.2. To sum up, the platform-specific frequency, even for non-operational HC leaks, is valuable in QRA studies. Furthermore, since this model can be used combined with the Risk OMT model to calculate platform specific frequencies for all types of HC leaks, it has the value of potential use.

Finally, the biggest criticism of the developed model may be related to the difficulty of getting relevant data for the model. The generic data for the model will be failure rates of equipment or system estimated through inspections or from statistics. In case of failure rates, since there is no particular way to measure the damage rates, finding a proper way can be difficult (but possible) for some technical degradations such as corrosion and erosion and may be impossible for some technical degradations. If failure rates are estimated by statistical data—for example, previous leak frequencies due to erosion—the problem seems easier but there remain other troubles such as double counting and the small number of leak occurrences available for statistical use. This is explained in detail in Chapter 8.3.

8.2 Generic vs. Specific

To determine the frequency of HC releases in offshore QRA studies, “generic” frequencies (which are based on the statistics of previous HC leaks) have been traditionally used and the different causal factors of the releases have not been analyzed (Sklet, 2006). For example, DNV developed a methodology for estimation of HC leak frequency. This methodology provides the expected HC leak frequency depending on the type and number of equipment on an installation (DNV, 2012). Consequently, if two installations have the same types and number of equipment, the expected frequencies estimated by the methodology become the same, regardless of the status of safety barriers on each installation. Such an approach does not account for inspection history, actually installation condition, or installation maintenance practices. Thus, evaluating whether introduced measures for HC leak prevention are sufficient or more safety barriers are needed is difficult.

With this background, BORA-Release and the Risk OMT model focused on causal factors of the leaks and sought to estimate the “platform-specific” leak frequencies by evaluating the status of the identified causal factors and barriers of a certain platform (Aven et al., 2006; Vinnem et al., 2012). Since they focus on operational leaks that are caused by human interventions, the usefulness of the platform-specific frequency for those leaks is intuitively understandable.

On the other hand, non-operational leaks, the concern of this project, are directly caused by technical problems. Thus, estimating leak frequencies depending on the equipment type and amount may seem reasonable. In other words, it may be considered that it is not meaningful to apply the platform-specific leak frequency to non-operational leaks. However, the findings through the investigation of previous leaks in this project show that many of the RIFs are relevant to human, organizational, and cultural aspects even though the initiating events are technical issues. In case of A-type (technical degradation) leaks, the common RIFs are age of equipment, PM, CM on previous leaks, and MoC, all of which are relevant to the operational condition of a certain platform, not a general technical condition. Therefore, this finding makes it meaningful to estimate the platform-specific frequency, not the generic frequency, of leaks caused by technical issues, by assessing the status of the RIFs and barriers on a certain platform.

8.3 Quantitative use of the model

The quantitative use of BORA-Release and the Risk OMT model is explained in Chapter 5. Since the model of this project builds on previous work in BORA-Release and the Risk OMT model in light of RIF models as well as the score and weight of RIFs, the same method of calculating scores and weights of RIFs can be applied.

However, there is a question mark on the generic frequency data to be used. For example, HEP is used as a basis in the Risk OMT model, and changed into the platform-specific leak frequency depending on the status of the RIFs. In case of the developed model in this project, the frequencies/probabilities of system failures with regard to technical degradation are needed. Sklet et al. (2006) suggested the use of the failure rate function of the gamma stochastic process for corrosion. According to the study, the time to HC leak due to corrosion is:

$$t_{release} = \frac{q_0 - q_{release}}{d}$$

q_0 denotes the wall thickness at time t_0, and $q_{release}$ denotes the wall thickness when release is expected to occur if there is no safety barrier. The damage rate d is unknown, but can be predicted by using measurements from inspections. In a similar way, time to failure and failure rate could be calculated for some other technical degradation.

A problem can arise when the damage rate is hard to measure through inspection—e.g. in case of valve sealing degradation and bolt tensioning. For these degradations, the use of statistical data is indispensible and there are difficulties. First, the number of a certain type of leaks is quite small for statistical use. According to Vinnem and Røed (Subitted for publication), only two HC leaks were caused by valve sealing degradation and only one leak was caused by flange gasket degradation in the NCS during 2008-2014. This could be a limitation because the small number of occurrence of events increases the sensitivity of the result to a single event and, hence, increase the possibility to have an error. Second, there is a risk of double counting leak frequencies. Since the frequency of initiating events is hard to know (technical degradation itself is not reported), the frequency of “leaks” caused by an initiating event could represent the frequency of an initiating event. If the leak frequency is calculated with this wrong type of data through the leak scenarios in Figure 7.1, the resultant frequency will be significantly less than the real leak frequency. To prevent this, the frequency of an initiating event should be taken, but, again, this is difficult in reality.

The main concern is the data for initiating events; however, since there are two more events in the developed leak scenarios, the data for those events should also be taken into account. It is hard to specify the data for “another event to trigger a leak” because the event is not fully examined in this project; however, for “failure to detect the technical degradation,” easier access and use of adequate data is expected: Since detection is carried out by working personnel, HEP could be applicable. Alternatively, an operating company (the expected user of the model developed in this work) could estimate the failure probability of detection based on their experience.

8.4 Alternative approach

Existing models or alternative approaches for estimating HC leak frequency and their advantages and disadvantages compared to the model of this project are discussed here.

First, as mentioned several times, the DNV model has been widely used to estimate HC leak frequency in the Norwegian offshore industry. The expected leak frequency is calculated by the DNV model regardless of leak types (operational or non-operational) based on the statistical data. Thus, the strong point is fast and easy process for leak frequency prediction. Equipment type and number on an installation are the only information needed to carry out the method DNV suggested. However, the estimation is very generic, and thus operators are not motivated to select materials that more reliable nor to improve maintenance and inspection practices. As a result, efforts to improve this kind of “conventional” QRA models have continued.

One effort was the work in the Risk OMT model, and Safetec suggested a method using the Risk OMT model for operational leaks and the DNV model for non-operational leaks. The method can be briefly explained as follows according to Safetec (2014): The HC leak frequency for a segment (here, segment means a group of different types of equipment which work for one common function) on an installation is first estimated using the DNV model, and the proportion of operational and non-operational leaks is determined depending on which types equipment consisting of the segment. Then, the HC leak frequency calculated by the Risk OMT model replaces the fraction of operational leaks. For instance, if the HC leak frequency for a segment calculated by the DNV model is 0.01 leak per year and the fraction of operational leaks is expected to 40% (accordingly, the proportion of non-operational leaks is 60%) for the segment, 0.006 leak per year becomes the result of the DNV model. Then, the result from the Risk OMT model replaces the left 40% (say, 0.005 leak per year is estimated using the Risk OMT model.), and thus the final HC leak frequency for the segment will be 0.011 leak per year. For an entire installation, the leak frequencies for all segments on the installation are added. The logic of this method is that time and cost for leak frequency estimation can be saved by calculating the "generic" frequency for non-operational leaks which are less relevant to a particular condition of an installation while the estimation is also reliable by calculating the "platform-specific" frequency for operational leaks. Furthermore, by combining two already developed methods, verification process for the Safetec method will be simple, and thus time and cost can be saved.

However, the developed model in this project built on the belief that consideration of specific condition of a platform is needed even for non-operational HC leaks, and verified that by identifying the RIFs for non-operational leaks through investigation into previous leak incidents. The same idea can be found in the recommended practice from API (2002). Although this practice does not only deal with HC leaks, it suggests the basic elements for developing and implementing a Risk-Based Inspection (RBI) program, to prevent failures of a system or equipment and the consequences of the failures in the HC and chemical process industry. It claims that failure frequencies of equipment (including the failures leading HC leaks) are estimated depending on the damage rate of material of an item and effectiveness of inspection program. This is in accordance with the finding of this project; the specific RIFs for technical degradation are associated with the damage rate and the common RIFs are relevant to maintenance and inspection. More detailedly, the specific RIFs can be classified with two characteristics: 1) design solution with margins and 2) usage of the system in relation to design limitation. The damage rate is decided by these two types of specific RIFs. The difference of the API's recommended practice with the model of this project is that it more focused on inspection programs (the interval, method, and etc.) rather than accurate frequency estimation. Although it cannot be directly used as a frequency model, the suggested two factors, damage rate of an item's material and effectiveness of inspection program, can be used for modeling in QRA.

8.5 Design error

According to the PSA (2011), design was pointed out as a critical cause of HC leaks. The study considered design with two aspects: as a general cause and as a direct cause of HC leaks. Design was discussed as a direct cause in Chapter 7.2 during modeling in this project, which was called “design error.” On the other hand, design that does not directly cause a leak but that can be still considered as a root cause is called “unfortunate design.” Unfortunate designs contribute to leaks occurring in several ways, such as poor conditions of maintenance or inducing an operator's mistake. In fact, 50% of accidents have at least one of their root causes in the design (Kinnersley & Roelen, 2007). Therefore, although this paper only focused on design error (the immediate cause of HC leaks), the effect of unfortunate design is also significant in the occurrence of HC leaks and further studies are needed for this.

Another topic pertaining to design is when to work on design errors. If safety and cost are considered, the answer is of course the design phase. Since the design phase takes place before construction, corrective action is easier and less costly when a design error is found. However, the model developed in this project dealt with design errors in the operating phase because: 1) the expected users of this model are operating companies, and 2) corrective action should also be taken on installations already operating offshore if they have design errors. Therefore, the RIFs for design error were identified with consideration of the operating phase. If an analysis focuses on the design phase, the RIFs should be different.

Finally, some limitations examining design errors are discussed. The main limitation was using incident investigation reports to determine RIFs. Even though the information in investigation reports was valuable for identifing the RIFs for technical degradation, it was not the case for design errors, since many accident investigation reports do not deal with design errors in depth. Consequently, the RIF identification for design errors was based on the relevant literature, and leak scenarios from design errors to a leak were not identified in the present model. Therefore, more studies are needed to verify whether the identified RIFs are suitable and to establish adequate leak scenarios, and the discussion provided in this chapter was mainly associated with leaks caused by technical degradation, not design error.

9 Conclusion and Further work

The model for HC leaks caused by technical degradation (A-type) and design errors (E-type) were built separately. In case of A-type leaks, the leak scenarios were developed using a generic event tree, and the risk influence diagram was made for each initiating event of the type A. However, these initiating events are relevant to each other, in that they were all technical degradations, thus sharing four common RIFs:

- age of equipment, PM, CM on previous leak, and MoC

The common RIFs are more relevant to the cultural aspect rather than technical issues; in particular, MoC is a more general factor that can be applied to operational leaks as well.

Specific RIFs on each initiating event are as follows:

- compliance of seal material requirements and thermal/pressure cycling for degradation of valve sealing (A1)
- temperature and working condition for degradation of flange gasket (A2)
- vibration and temperature, and compliance of installation/tightening requirements for loss of bolt tensioning (A3)
- fatigue limit of materials and cyclic loading for fatigue (A4)
- steel type, and corrosive fluid and temperature for internal corrosion (A5)
- steel type, insulation and coating, and environment for external corrosion (A6)
- capacity to sand production, and design and location for erosion (A7)

Some common ground can be found in the specific RIFs. The identified RIFs can be classified based on two characteristics: 1) design solution with margins and 2) usage of the system in relation to design limitation. Between the two RIFs for fatigue, for instance, the fatigue limit of materials represents the first feature and cyclic loading corresponds to the second.

RIFs on other causes (A8) were not identified in this project because the initiating event, other causes, is not the specified event. Nevertheless, the common RIFs can be still used because it is also in the technical degradation category.

In case of E-type leaks, leak scenarios were not developed. RIFs on design errors are divided into two levels as follows:

- complexity of equipment, manufacturer, and quality assurance in the equipment level
- complexity of system, design firm, risk assessment, and time/cost constraints of project in the system level

The characteristic of the RIFs identified in this project, either for technical degradation or design error, is that many of the RIFs are relevant to human, organizational, and cultural aspects even though the initiating events (technical degradation and design error) are technical issues. This finding makes it meaningful to estimate the platform-specific frequency, not the generic frequency, of leaks caused by technical issues, by assessing the status of the RIFs and barriers on a certain platform.

The quantitative use of this model is possible on adopting the concepts of scores and weights of RIFs used in BORA-Release and the Risk OMT model. Then, if this model is combined with the Risk OMT model which covers the leaks due to human intervention, the platform-specific frequency can be estimated for all types of HC leaks.

Further studies need to be carried out to use this model quantitatively, such as how to evaluate the status of the newly identified RIFs in this thesis for scoring, how to weight the RIFs, and how to get generic frequencies adequate for this model. Also, more work is needed for design error causing leaks in order to verify that the identified RIFs are suitable and to establish adequate leak scenarios.

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Appendix A. RIFs and relevant incidents

Table A.1 Identified RIFs and the relevant incidents

RIF category	Identified RIFs	Relevant incidents
Common	Age of equipment	03500, South Pass 67 platform A, Unnamed 1, Unnamed 2
	PM	03484, 03500, 03527, 03534, 03584, 6B 5163 Houchin, 6B 5165 platform A, Hermosa, Ula P, Unnamed 2, Unnamed 3
	CM on previous leaks	03500, 03522, 6B 5165 platform A, South Pass 67 platform A, Ula P, Valhall PCP
	MoC	03484, 03518, Hermosa, Unnamed 2, Unnamed 4
A1	Compliance of seal material requirements	03500, Unnamed 4
	Thermal/pressure cycling	Unnamed 4
A2	Temperature	
	Working condition	Unnamed 1
A3	Vibration and temperature	
	Compliance of installation /tightening requirements	
A4	Fatigue limit of material	
	Cyclic load	03518, Unnamed 2
A5	Steel type	Ula P
	Corrosive fluid and temperature	03522, Hermosa, Ula P
A6	Steel type	03527, 03553
	Insulation and coating	03527, 6B 5165 platform A
	Environment	03484, 03527, 03534, 03553, 6B 5165 platform A
A7	Capacity to sand production	Oseberg A, South Pass 67 platform A, Unnamed 3
	Design and location	Oseberg A, Unnamed 3

Appendix B. Description of RIFs

Table B.1 Description of RIFs

RIF category	Identified RIFs	Description
Common	Age of equipment	The effect of equipment age on the degradation. Even though the ages of two pieces of equipment are the same, the scores can be same depending on the "critical" ages of the equipment.
	PM	Preventive maintenance. It includes inspection/maintenance program, competence of technician, accessibility for PM, and compliance of inspection/maintenance program.
	Inspection/maintenance program	The effectiveness of inspection/maintenance program.
	Competence of technician	Technician's qualifications, experience, and knowledge.
	Accessibility for PM	The factors to affect the accessibility for PM: barriers to access equipment and the location of equipment.
	Compliance of program	How well the established inspection/maintenance program is complied. It is related to the practice and culture of an operating company.
	CM on previous leaks	How adequate the corrective maintenance was on the relevant previous leaks. If there was no previous leak on an installation, the score is regarded as A.
	MoC	The effectiveness of management regarding any changes including equipment and process changes. If there was no change on an installation, the score is regarded as A.
A1	Compliance of seal material requirements	Compliance of the requirements of the selected/used seal material. It is mainly related to the applied pressure/load and temperature to the seal.
	Thermal/pressure cycling	When a seal is in use, how many times the seal is exposed to thermal/pressure cycling and how large the temperature/pressure variation is.

A2	Temperature	How high temperature a gasket flange is exposed to in working condition.
	Working condition	Conditions to affect the degradation of gasket flange, including gasket compressive stress, internal fluid type, pressure, gasket geometry, and flange rigidity.
A3	Vibration and temperature	How large vibration and high temperature bolts are exposed to during operation.
	Compliance of installation /tightening requirements	Compliance of the requirements when installing and tightening bolts.
A4	Fatigue limit of material	The maximum cyclic load that the material in question can handle, with regard to fatigue. This is given depending on the material type.
	Cyclic load	How large and frequent cyclic load is applied to the material in question during operation.
A5	Steel type	How strong the used steel type is against corrosion.
	Corrosive fluid and temperature	Does the piping of interest contain any corrosive fluid, and how high the temperature of the place is.
A6	Steel type	How strong the used steel type is against corrosion.
	Insulation and coating	Is coating adequate to prevent corrosion, and is insulation adequate to prevent CUI.
	Environment	Environment covers corrosive substance, temperature, residual substance, and construction details.
A7	Capacity to sand production	Whether the system or pipe is used for sand production, and if is, the capacity to sand production.
	Design and location	Design of and location in piping with regard to erosion. For example, erosion occurs at a bend of piping since sand can easily accumulate there.