Faculty of Science and Technology

MASTER'S THESIS

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EXECUTIVE SUMMARY

The oil and gas industry at the Norwegian Continental Shelf (NCS) is today facing hundreds of subsea wells that will need Plug and Abandonment (PnA) operations in the nearest future. Due to a marked where costs have escalated rapidly over the last half decade, a cost and efficiency strategy for plugging and abandoning these wells had to be made (Statoil 2014).

Halliburton is today in the process of developing an integrated project between different third parties in order to plug and abandon subsea wells in a more efficient and cost friendly manner (Halliburton, Petrobas et al. 2014). Seeing that we are performing the same operation on hundreds of wells, copying Hazard Identification Analysis (HAZID) is an easy way out; but can lead to major incidents and accidents if hazards related to use of new technology, such as subsea PnA, are not identified. In order to prevent this, the first objective for this thesis was to develop a new model for identifying unwanted events. This model is based on events (A) leading to future consequences (C). Moreover, the model is based on Anticipatory Failure Determination (AFD), which is a method where creative solutions to technical problems are created. The fundamental idea with AFD is to ask inverted questions which answer how we are able to create failures. The question "how can we make this operation fail?" is asked throughout this thesis in order to create different events leading to unwanted consequences. In addition, this thesis has developed a four step procedure on how to use the model. The steps involve forward and backward ways of identifying unwanted events. The backwards way are analyzing from consequences to events, while the forwards way are analyzing from events to consequences.

The second objective for this thesis was to use the model we have developed to create failures in subsea PnA. This has been done on parts of the operations that are involved in a subsea PnA, and six new unwanted consequences have been discovered.

The model developed is also applicable for other areas apart from subsea PnA where basic knowledge of the operation, design or scenario already exists. In this thesis, the model is also illustrated for an everyday example, as well as to subsea PnA operations. For further implementation of the model into the oil and gas industry, additional development is required. However, the model is a good start for further development.

PREFACE

A three year master study has finally come to an end, and I am so happy to finally see the light at the end of the tunnel. Working offshore and studying for the masters has not always been a bed of roses, especially not those times where offshore trips and work related courses has held me back from school for over months. However, I am today glad I got a third year to take the two leftover exams I had, and of course, write this final master thesis.

I would like to thank my family for all the support I have been given the last years, especially from my driven father always talking about the "motivational motor" inside me. I would like to thank my brother in law, Bård Arve, for text editing and feedback. And of course to my boyfriend Kjetil – special thanks to you for encouraging me throughout the semester, reading through the whole thesis giving me great feedback, and helping me to understand technical aspects of plug and abandonment procedures.

Last, but certainly not least, I am forever thankful for the great support, creative thinking when helping me to develop the thesis, and constructive help that I have been receiving from my faculty supervisor, Roger Flage, throughout the semester. In addition, I am grateful to Jørn Tore Giskemo in Halliburton for giving me the chance to write this thesis about subsea plug and abandonment – a field which is of great importance in the nearest future.

ABBREVIATIONS

AFD – Anticipatory Failure Determination

BOP – Blowout Preventer

ES – End State

ESD – Emergency shutdown system

ERRV – Emergency Response and Rescue Vessel

FMEA – Failure Mode and Effect Analysis

IE – Initiating Event

NCS - Norwegian Continental Shelf

MS – Middle State

HAZID – Hazardous Identification Analysis

HAZOP – Hazard and Operation Analysis

PRM - Project Risk Management

(P)PnA - (Permanent) Plug and Abandonment

PSA – Petroleum Safety authority

PSL – Product Service Line (Halliburton)

QRA - Quantitative Risk Analysis

TRIZ – Theory of Inventive Problem Solving

WHIM – Wellhead Interface Module

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1. INTRODUCTION

1.1 BACKGROUND

The activity level on the Norwegian Continental Shelf (NCS) has decreased the last year. Many rigs are in dry dock and their rental rates are decreasing as a result of the operators' will to save money (Sysla 2015). Before the decreasing trend started, the activity level on the NCS had reached the top, and the operators had a high demand for rigs resulting in sky-high prices. Due to the high activity level we have experienced, we are today facing a time where 500 subsea wells are in need to be plugged and abandoned (PnA) (Statoil 2014). The conventional PnA process is a rather expensive operation where a fully equipped rig with all involved personnel is needed. Even though there are more rigs available now than there were a year ago, we are still facing hundreds of subsea wells to plug in the nearest future, and cost and efficiency are key elements to win contracts. Halliburton Project Management (HPM) is in the development of making an integrated project between different third parties to increase efficiency and lower cost and time consumption. This type of project will be a large scale project and will be the first of its kind on the NCS. Halliburton has executed a similar subsea PnA project in Brazil in November 2014, but on a much smaller scale. The size of the project on the NCS is of such a magnitude and complexity that compared to the project in Brazil we can say that this project is a first worldwide (Halliburton, Petrobas et al. 2014).

Risk management is mandatory for companies all around the world. It is required by laws and regulations, but also to ensure for the well-being of employees, to protect and care for the environment and to ensure the existence of the company. Many different risk management techniques are being used today, such as Hazard and Operation Analysis, Failure Mode and Effect Analysis, Hazard Identification Analysis and Quantitative Risk Analysis. These are all methods that have been used for some time, and are good methods when analyzing what could go wrong (Aven 2008). However, conversations with the industry have led us to believe that some of these techniques are not involving or engaging all the participants that are contributing to the risk identification analysis. Some of the participants may think that they "know it all" as they have a lot of experience. Some may suggest copying the last wells' HAZID as the risks are "probably the same". Because of this mindset, risks may be left out due to lacking engagement from participants. In order to change and challenge this mindset, a modification of future risk identification techniques is needed.

When it comes to subsea Plug and Abandonment (subsea PnA) – an operation that has never been executed on the NCS before, it can be challenging to analyze up front what could go wrong. With subsea PnA we mean PnA performed riserless with a vessel. With new technology, new parties involved and a different organizational structure, we can say what a former US secretary of Defense once said "we don't know what we don't know", meaning that scenarios or situations can occur that have not been thought of which can cause harm to human life, technology and operations. A method for finding failures before the failure finds us is developed and is based on the Russian method of Inventive Problem Solving, TRIZ (Barry, Domb et al. 1996). TRIZ is a comprehensive tool for solving problems, and as a part of the TRIZ process we find the Anticipatory Failure Determination, AFD, which is the part where we try to find the failures, before the failure finds us. AFD is a method where creative solutions to complex technical problems are created. The core idea of AFD is not to ask the question "What can go wrong?", but to rather ask inventive questions like "How can I make this go wrong?"(Kaplan 1997). It is probably not surprising that finding failures related to the scientific field one have never encountered before is border line impossible. However, with the AFD process one is able to invent problems and think outside the risk analysis box. It is not necessarily that we find failures never encountered before – most likely not, but with the use of AFD we are able to look at problems and operations from a different perspective.

1.2 PURPOSE

The purpose for this thesis is to develop a model to identify unwanted events with a basis on Anticipatory Failure Determination (AFD). The second purpose for this thesis is to use the developed model to try and identify new unwanted events in parts of the operation for subsea Plug and Abandonment.

1.3 SCOPE AND LIMITATIONS

The model in this thesis is developed on the foundation of AFD analysis, and the main question we are asking in this thesis is "How can we make this operation go wrong?" The model uses "initiating events, IE" instead of "events" and "End states, ES" instead of "consequences", which are also common terms. Further, the model distinguishes between old and new initiating events, and old and new end states. This means that every scenario has initiating events that eventually will lead to some end states. If we make a modification to the scenario, the initiating events and end states we had will turn "old", and the modification we make will create new initiating events and as a result of the "new" initiating events; "new" end states. A four step procedure is developed in this thesis in order to identify unwanted events from different perspectives.

The AFD process is a rather comprehensive and time consuming process. Going through the steps in the method thoroughly one by one exceeds the time frame that is given to fulfill a master's thesis. As a result, the analysis has been executed with inspiration of the AFD method; nevertheless AFD has been used to a certain extent where possible. The AFD software, which is an important part of the AFD process, is not within reach during the thesis progression, and is hence not in the scope of work. This thesis only seeks to find failures related to the six pre-selected end states written in the HAZID from the conventional PnA, and no further analysis method has been used other than the presented HAZID. It is beyond question that subsea PnA is an extensive operation where many unforeseen scenarios may occur. Today, when performing conventional PnA, unforeseen scenarios still occur and the industry has been plugging wells for decades. The analysis is thus narrowed down to pre-selected end states taken from a known HAZID performed with a conventional plug and abandonment operation.

There are many initiating events leading to different end states, and technical and operational knowledge is needed to invent them. In this thesis, finding initiating events and end states is limited to the writer's knowledge for the field of subsea plug and abandonment. It is not stated that the initiating events or end states that are created in this thesis are the most correct, but one of most likely many. However, the scope was not to find *all* initiating events or end states, but to illustrate the model. Further, this thesis does not provide any preventive measures for the end states that are created in the subsea PnA case, as this was not within the scope.

1.4 STRUCTURE OF THESIS

The first part of this thesis, chapter 2, covers some basic information about Halliburton and the Product Service Line (PSL) Project Management & Consulting, in addition to plug and abandonment – what it is and why it is performed.

The next part, chapter 3, covers background theory about risk definitions and risk descriptions. Further, it gives a brief in risk analysis, together with scenario analysis and the phenomena of the black swan. In addition, it contains fundamental theory about Theory of Inventive Problems Solving (TRIZ) and how it became what it is today. Further, it gives the reader information about the AFD and how this analysis is executed, which is of importance for the understanding of the coming analysis.

The fourth part, chapter 4, introduces a suggestion for a new model to identify unwanted events. In addition, the model is illustrated with an everyday example.

The fifth part, chapter 5, is the main analysis for this thesis. In this chapter we are asking the question "how can we cause this failure?" for different pre-selected end states in subsea PnA, and we are using the four step procedure that is developed.

The sixth part, chapter 6, gives a discussion about the developed model, areas of application, future implementation and strengths and weaknesses.

The seventh and last part of this thesis, chapter 7, provides a conclusion and some closing remarks.

2. HALLIBURTON AND PLUG AND ABANDONMENT

Halliburton was founded in 1919 and is one of the world's largest oil service companies. With headquarters in Houston, Texas and over 80 000 employees in over 80 countries worldwide, Halliburton serves the oil and gas industry throughout the process of locating hydrocarbons and managing the geological data, drilling and formation evaluation, construction and completion of wells and to enhance and optimize the lifespan of a production field. (Halliburton) Halliburton Scandinavia has its headquarters in Tananger with over 2000 employees.

Halliburton constitutes 13 product service lines (PSLs), where 12 of the PSLs are divided into two: Drilling and Evaluation Division and Completion and Production Division. The Drilling and evaluation division consist of the following PSLs:

- Baroid
- Sperry Drilling
- Wireline and Perforating
- Drill Bits and Services
- Testing and Subsea
- Landmark software and services

The Completion and Production division consist of the following PSLs:

- Cementing
- Completion Tools
- Production Enhancement
- Boots and Coots
- Artificial Lift
- Multi-Chem

The 13th PSL is the Consulting and Project Management (CPM) PSL that works cross-over the two divisions.

2.1 HALLIBURTON CONSULTING AND PROJECT MANAGEMENT (CPM)

Halliburton Project management (HPM) delivers well designs and complete well delivery. HPM take account for every aspect of the project and brings the entire Halliburton organization to work during planning, execution and close out of a well. HPM methods include risk and uncertainty management, technical limit focus, time- and cost estimation, and detailed scheduling. Experienced negotiation and management procurement, contracts and logistics help reduce risk and cost of operation.

Most people intuitively understand what project managers do, but they don't necessarily understand everything that goes into a project lifecycle, as the list of activities in a project is extensive. Halliburton sells the project management "packages" in three ways. Figure 1 below illustrates the three packages and what they offer. Basic Packaged Services is the basic package where only fundamental activities are offered. Moving from left to right, the next package is a subset of the previous one. In other words; Advanced Packaged Services contains everything that Basic has, plus more. And Integrated Project Management contains everything that Advanced has, plus more. It is mandatory that Basic and Advanced packages are provided to clients when 4 PSLs or more are working on a job together and generating more than 60 million dollars per year. The package that Halliburton provides depends on the number of PSLs that are working on the project, the complexity of the project and the economic value of the project.

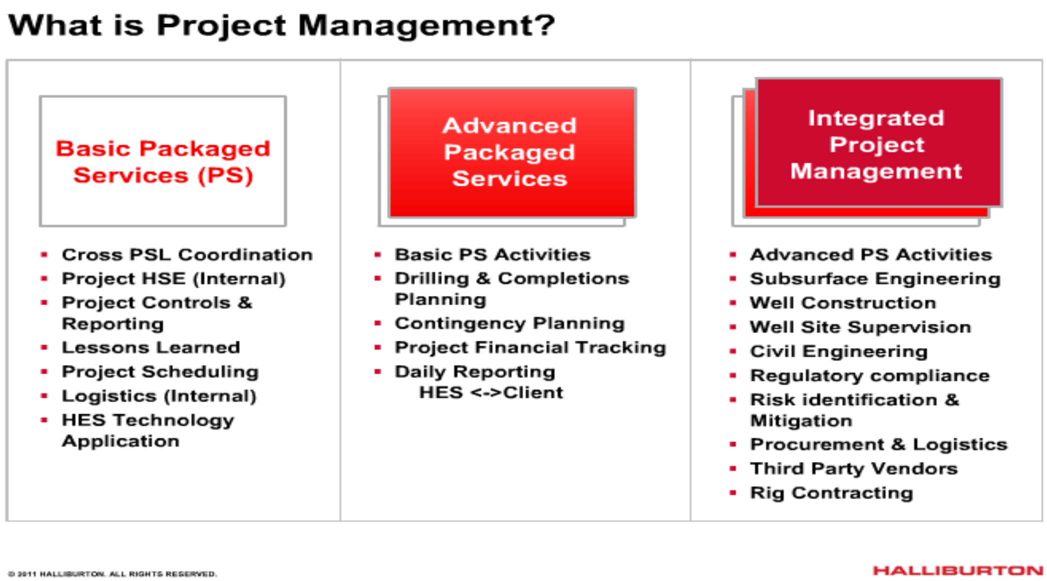

FIGURE 1 WHAT IS PROJECT MANAGEMENT (HALLIBURTON)

As Integrated Project Management is being used for the Subsea PnA project, Basic and advanced packages will not be further discussed in this thesis.

2.2 CONVENTIONAL PLUG AND ABANDONMENT

The purpose of a PnA is to create barrier to seal of the reservoir (pay zone), potential leak zones and fresh water zones to ensure that the well will do no harm to the environment after abandoning it. This is done by pumping cement plugs down the well that cover the potential zones. There are mainly three types of abandonments (NORSOK 2013):

- **Temporarily abandonment**
  - Temporarily abandonment is executed when the operator is to re-enter the well again when performing, for instance, enhanced oil recovery operations.
- **Permanent abandonment**
  - Permanent abandonment is executed when the lifespan of the well has come to an end, and the operator is not interested in doing further work on the well.
- **Permanent abandonment of a section in a well**
  - Permanent abandonment of a section in a well is done when performing sidetracking or slot recovery.

This thesis will concentrate on permanent PnA operations, and temporarily abandonment will not be further discussed.

From 1966 to May 2013 there were drilled 5450 wells altogether on the NCS. Today we are faced with a conservative number of 3000 wells that is in need of permanent PnA. The conventional PnA process is a rather time consuming and expensive operation. Out of experience we know that a PnA operation can take days to months to execute, all the way from 20 to 60 days, depending on complexity of the well, technology and weather. Having this in mind, Statoil has estimated that it can take up to 40 years to plug all the wells on the NCS (Statoil 2014).

2.2.1 CONVENTIONAL PLUG AND ABANDONMENT PROCEDURE

The procedure for PnA operations performed using a semi-submersible, jack-up or a platform is dependent on the well, but is normally in close range of the following steps (Halliburton 2014):

1. Connect to Xmas tree (XMT)
2. Kill and secure the well
3. Cut tubing
4. Circulate wash train to fully clean the well

5. Install tubing hanger plugs
6. Run Tree Running Tool (TRT) and retrieve XMT
7. Run Blowout Preventer (BOP) and Marine Riser (MR)
8. Pull tubing hanger and tubing
9. Log cement behind casing
10. Pump primary and secondary cement plugs and verify
11. Cut and pull any other casing strings in the well that cover formations containing hydrocarbons or that has potential to flow
12. Set surface cement plug
13. Cut and remove wellhead

As stressed, the conventional way of performing a PnA operation is expensive and time consuming. The operation is especially dependent on weather conditions regarding heavy lifts such as running and retrieving the BOP and XMT.

2.2.2 RISK MANAGEMENT IN CONVENTIONAL PNA OPERATIONS

For PnA operations, hazardous events are identified through Hazard Identification Analysis (HAZID). HAZID is a systematic method to examine a system or operation where risk, and challenges towards risk are identified. HAZID is being used each time a new well is to be PnA.

The table below shows an extract of the HAZID performed on the Camelot Plug and Abandonment project on the UK sector. The table only shows activities for PnA and not activities prior or after plugging the well. The table does not show the full list of activities for PnA either, but an extract of them. This HAZID will be used later in this thesis, as a foundation for the coming analysis and development of model. As we can see from the table, we have activities, hazard descriptions, consequence descriptions and control measure. It is the row of consequences that will be used later when developing the model and performing the analysis. The full HAZID is attached in appendix A.

Activity / Description	Hazard Description	Consequence Description	Control Measures Required
Swap Cap Removal	Trapped pressure below swap cap	Release of pressure	Pressure bleed off procedure
General Hazards: Adverse weather	Fog, high winds, sea state, lightning	Potential personnel injury due to adverse	Weather monitoring. Helicopter limits. Operating limits. Daily tool box talks.

		weather conditions. Schedule delay	ERRV operations
General Hazards: Vessel Collisions	Supply boats Passing ships Fishing/seismic vessel nearby	Potential damage to vessel / installation	Vessel marine packages / ERRV operations
General Hazards: Helicopter Operations	Helicopter collision with installation	Personnel injury Loss of helicopter	Standard heli-ops procedure Adverse weather limitations
Set up equipment and function test	Use of airlines Existing pressure in equipment Chemical/fluids spill	Injury to personnel Damage to equipment	Secure air lines Bleed off pressure prior to start Flush through equipment prior to operations
Downhole	Unable to obtain required well isolations	Schedule delay until isolations in place	Single cement barrier in place Seawater column provides secondary barrier Xmas tree remains in place until above barriers are in place and tested
Slickline operations	Tools stuck in well	Schedule Delay	Reference to Halliburton Risk Assessments Regular pick-up weights to be taken
Hydrate Formation	Stuck tools in well	Schedule delay	Lengths of toolstring to be supplied Trained and competent personnel Lengths to be physically checked and measured
Leak from piping / equipment	Loss of containment	Spillage of OBM/chemicals onto installations Spillage to sea	All fluids contained within break tank Usage/discharge volumes recorded daily No contaminated wellbore fluids discharged to sea

TABLE 1: THE TABLE SHOWS AN EXTRACT OF HAZARD ACTIVITIES, THEIR DESCRIPTIONS AND CONTROL ACTIVITIES FOR THE CAMELOT PNA PROJECT ON UK SECTOR

The oil price is hard to foresee, but what is known is that is has been sky high the last years. According to Macrotrends (2015) the oil price has been above $100 from 2011 to 2014. In a historic perspective, $100 a barrel is very high. In February 2007, the price of crude Brent oil was $58. Further, in the 1990s the price for Brent crude oil was stable at plus minus $30, and for 10 years this was normal. When we hit the Millennium, the oil price had an increasing tendency and from the start of year 2000 and up until year 2008, the price gradually increased up to $130. This was what was called an “all-time high” however, the price didn’t last long on that level, and the financial crises that hit the world in late 2008 contributed to an oil price down in the range of $40 (Macrotrends 2015). One can say that the oil price tendency can be resembled with a rollercoaster, and you never know what way it will go.

As mentioned, from 2011 the price has been high, and the activity on the NCS has, as a result, been an all-time high as well. In this time period, there has been a shortage of jack-ups and semi-submersibles, and the operators have been screaming for more rigs. The operators wanted to drill more wells, and at the same time also PnA the wells that were coming to an end on the production. A PnA operation is, seen through the operators’ eyes, extremely expensive as one will never get profit out of the operation. Drilling a development well, on the other hand, will result in profit for the operator. Rigs which have high day rates are thus more likely to be used to drilling, than plugging. A demand for a rigless PnA operation was as a result raised.

When writing this thesis, the oil price is down in $50 and we can ask ourselves if a rigless PnA is as demanding today as it was in 2013 when Halliburton Project Management initiated the project “Subsea PnA”. The current situation with the request for rigs are not the same as it was two years back, and lots of rigs are in the dock waiting for work. Even the day rates on the rigs have decreased due to the reduction in demand (offshore.no 2015). However, what we do know is that the industry is a rollercoaster and as far as we know, the oil price and the demand can increase by the double in one year. The subsea PnA project gives the operators a more cost reducing and efficient operation – no matter what prices and demands are. As stressed, subsea PnA has not been done before on the NCS. Taking account for the large-scale project it is, it has never been done other places in the world either. The fact that this is “a first” brings uncertainties and high risk both technically and economically. The biggest difference between conventional PnA and subsea PnA is that it will be performed from a vessel and not a semi-submersible or a platform. The detailed procedure for how to conduct the plug and abandonment is more or less the same, with some minor distinctions. Nonetheless, performing an operation from a vessel opposed to a drilling rig is different in terms of how equipment works. The architecture of the vessel regarding the connection from the vessel to the seabed is dissimilar from a semi-submersible or a platform. Semi-submersibles or platforms operate risers – a metal pipe that is connected from the rig to the wellhead. The vessel, on the other hand, will not have any riser, but will use a riserless mud recovery system. Primarily this means that the returning fluids from the well will be pumped up to surface through a hose and not through a metal riser, with a subsea booster pump to help the fluid move. Figure 2 below shows the vessel with drill pipe string into the well with hose and subsea pump. Figure 3 below shows a close-up of the subsea equipment.

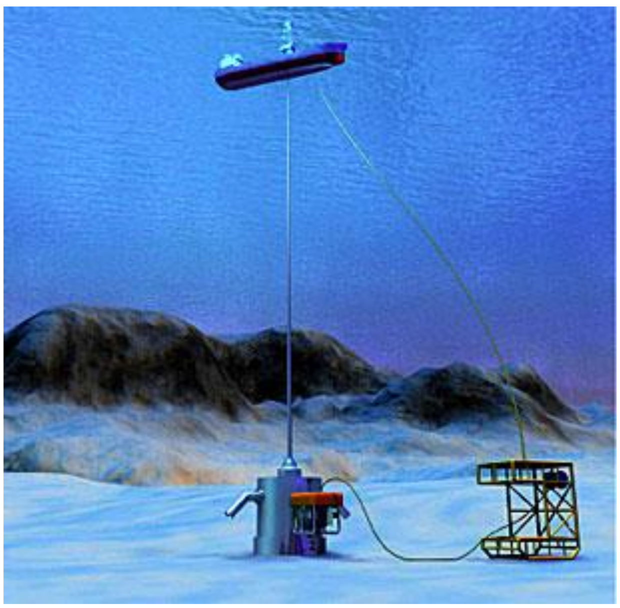

FIGURE 2: VESSEL WITH SUBSEA EQUIPMENT (HALLIBURTON, PETROBAS, WELLTEC 2014)

FIGURE 3: CLOSE-UP ON SUBSEA EQUIPMENT

A hose compared to a metal pipe is seemingly more fragile, and risk related to the matter will be discussed in the analysis in chapter 5.

The project today is only at a study phase, and the project has not been sanctioned by the client, yet. The finalization of the project plan is ongoing while writing this thesis.

3. THEORY

This chapter includes theory that is important for the understanding of this thesis.

3.1 THE RISK CONCEPT

3.1.1 RISK AS A CONCEPT

Risk is a word most people have an understanding of. The word risk is for most people subjective, meaning that one person may look at risk differently than another person. In most cases, risk is related to something bad or unpleasant. Merriam-Webster Encyclopedia defines risk as "*the possibility that something bad or unpleasant (such as an injury or a loss) will happen*"(Merriam-Webster). Here it is referred to something bad, unpleasant, injury and loss, and in this case risk is something negative. However, risk can also be related to something positive. Another definition of risk is "*Risk is a situation where something of human value (including human themselves) is at stake and where the outcome is uncertain" (Rosa 1998).* Further, Aven and Renn gives a similar definition of risk when saying that "*Risk is uncertainty about and severity of the consequences (or outcomes) of an activity with respect to something human values" (Aven and Renn 2009).*

Aven (2010) combines different definitions and states that *"Risk comprises events (initiating events, scenarios), consequences (outcomes) and probabilities. Uncertainties are expressed through probabilities. Severity is a way of characterizing the consequences".* From this articulation Aven formalizes it by writing:

Risk = (A, C, P)

where A is the events, C is the consequences for the event A, and P is the associated probabilities.

A probability, P, is a way to express the likelihood of an event or consequence to occur. Probability doesn't necessarily give a good enough foundation for decision-making. We can interpret probability in the following way (Aven 2010):

1) The probability is interpreted as a relative frequency. $P_f(A)$ is the relative fraction of times the event, A, occurs if the situation was repeated an infinite number of times.

2) The probability, P, is a measure of uncertainty about future events and consequences, seen through the eyes of the assessor, and is based on some background knowledge or information.

There are many ways to define risk, however; from the two interpretations of probability above we have two ways to define risk:

I. We can define risk by using the probability in 1) and we define it by saying that Risk = (A, C, P_f), where A is the events, C is the consequences for the event A, and P_f is the relative frequency interpreted probability.
II. We can define risk by using the probability in 2) and we define it by saying that Risk = (A, C, P_s) where A is the events, C is the consequences for the events A, and P_s is the subjective probability (probability seen through the eyes of the assessor)

The concept of risk is in constant development, and the Petroleum Safety Authority (PSA) has recently revised their definition of risk; highlighting that risk is more than probabilities and historical events (Backe 2015). From January 2015 the concept of risk from PSA's perspective was defined as "*the consequences of the activities, with associated uncertainties."* (PSA 2015). This gives rise to say that risk = (C, U), where C is consequences for the event, and U is the uncertainty about C (will A happen and what will the consequences, C, be?). PSA states that "consequences" is a collective term for all the possible consequences related to the activity. The term is not only limited to final consequences, such as loss of lives, but is also including conditions or incidents that can result in this type of final consequence. The term "uncertainty" is related to the consequences, as well as to which incidents that can occur, how often they can occur and the potential damage they will cause in the sense of human life and health, environment and material assets (PSA 2015).

In this thesis we are going to concentrate on the definition of PSA, saying that risk is (A, C, U). With that said, the uncertainty, U, will not be looked at in this thesis, only events, A, and consequences, C. As it will be described later in chapter 3.3 and chapter 4 we will not use the notation A and C, but IE and ES.

3.1.2 RISK DESCRIPTION

The concept of "risk" has been defined above, and we are now going to introduce the risk description. As it is only the (A, C, U) perspective that is within interest for this thesis, the description to (A, C, P) will be left out.

As for the definition of (A, C, U) where we know that A is events, C is consequences and U is uncertainties, we can describe risk as (A', C', Q, BK). A' and C' are the descriptions of the events and consequences, Q is the description of uncertainty and BK is the background knowledge.

3.1.3 COMMON DEFINITIONS OF PROJECT RISK MANAGEMENT

According to Chapman and Ward (2001) the UK association for Project Management have defined risk in Project Risk Management (PRM) as "*Risk – an uncertain event or set of circumstances that, should it occur, will have an effect on the achievement of the project's objective*". The US Project Management Institute has defined PRM as "*Risk – an uncertain event or condition that, if it occurs, has a positive or negative effect on a project objective*". Both of these definitions are quite similar. However, what is different from the Merriam-Webster definition in chapter 3.1.1 is that these descriptions give room for "up-side"effects as well, not only the expected unwelcome "down-side" effects. Nevertheless, when thinking of Project Risk Management, there is always a tendency of thinking about risk as having a down-side effect.

PRM has a slightly different tone over the definition associated with risk, and from what is stated above we can say that it has either a negative outcome – a threat for the project, or a positive outcome – an opportunity for the project. Chapman and Ward (2001) call the former for threat management and the latter for opportunity management, and those two combined make up "Uncertainty Management".

3.2 RISK ANALYSIS

The intention with risk analysis is to disclose and identify potential hazards and threats in the system or operation, so they can be managed before they occur. There exists several risk analysis methods today. To name a few, Failure Modes and Effect Analysis (FMEA), Hazard and Operations Analysis (HAZOP), Fault Trees and Event Tree, and Quantitative Risk Analysis (QRA) are some of them. The similarity of the mentioned analysis methods are that they analyze the hazards and threats that we know of, and not the unknown hazards and threats. The above mentioned Risk Analysis methods will not be given further attention, as they don't have any directly contribution to this thesis. Quantitative Risk Analysis, on the other hand, will be reviewed.

There is a need of quantifying the risk, and this is done by Quantitative Risk Analysis. This is a method where the likelihood and the consequences of the scenarios are put into numbers. With QRA we can ask the questions below, and from them define and describe risk (Kaplan, Zlotin et al. 1999);

1. *What can go wrong?*
2. *How likely is it that it will occur?*
3. *If it would occur, what will the consequences be?*

The answer to question number one is called a failure scenario or a risk scenario, where it is assumed that there are multiple scenarios, and these scenarios are denoted S_i.

The answer to question number two is answered for each individual scenario, and the likelihood is denoted L_i.

The third question relates to the damages or consequences resulting from the scenarios, and is denoted X_i

The triplets of (S_i, L_i, X_i) is the well-known definition of risk given by Kaplan and Garrick in 1981. To achieve a mathematical set, the triplet is put in brackets, and for a complete set, a c is added to the brackets. We get the following definition:

$R = (S_i, L_i, X_i)_c$

By complete it is meant that all possible scenarios are identified, or at least the important ones (Kaplan, Zlotin et al. 1999). Further they state that completeness comes with the quantitative part of the analysis, where determining L_i and X_i are the important factors. However, the qualitative part, determining S_1 is the factor that gives the biggest contribution to Anticipatory Failure Determination (AFD), which is the analysis method being used later in this thesis, and S_1 will hence have the main focus.

3.2.1 QUANTIFICATION OF LIKELIHOOD L_I AND CONSEQUENCE X_I

L_i is the symbol for likelihood and gives us a number on how likely it is that the scenario, S_i, occurs, and is often given as a parameter of frequency. X_i is the symbol of the consequences and is captured quantitatively as for instance “fatalities”, “number of injuries” or “repair cost”. X_1 is, of course, dependent on what the scenario is.

There are different ways of how we can quantify L_1 and X_1. According to Kaplan (1997) we have the six following levels on quantification:

- Verbal
- Semi quantitative
- Point Estimate
- Bounding Estimate
- Probabilistic

- Evidence-based

Verbal quantification rates frequencies as "high, medium or low". The semi quantitative rates the frequencies from a scale from 1 to 10. It doesn't necessarily need to be from 1 to 10, but the main point is that it needs to be scale-based. Further, "point estimate" is a best guess numerical value for the frequency. The next quantification, the "bounding estimate" can be combined with the "point estimate". As for the "probabilistic" quantification, it is acknowledged that the exact value is not known for the given scenario. What is known and not known is hence expressed by probabilistic curves given by experts that have specific expertise on the area. The last quantification, "evidence-based" is carried out listing down all evidence items. The items are then processed through Bayes' theorem.

The intention of quantifying L_i and X_i is to better understand what type of scenarios that needs the most attention so that resources are used in the most efficient way.

3.3 SCENARIO ANALYSIS

Scenario analysis (SA) has been known for a long time and is an important factor in a decision making context. If scenario analysis is used in a correct manner, it can expose many important parts of a situation that would otherwise be missed out. SA tries to direct the situation and events in the correct way, meaning that it impacts important aspects of the situation in the future (Dutta and Babbel 2012). Scenario Analysis has two important elements; future states and current states. Future states are the evaluation of future possibilities with respect to certain characteristics, and current states are the present knowledge of the characteristics.

In any real world, the set of possible failure scenarios are immeasurable. There will always be identified more scenarios and subcases that weren't identified from the start. As stressed in chapter 3.3 the scenarios are denoted $S_{i,}$ and this answers the question "*what can go wrong?*" To find all possible scenarios can be a comprehensive process, so Kaplan (1997) introduced "The Theory of Scenario Structuring". This theory consists of eight different principles which are explained below and based on (Kaplan, Zlotin et al. 1999) and (Kaplan 1997)

3.3.1 THE PRINCIPLE OF S_0 (AS PLANNED SCENARIO)

The principle of S_o can also be described as the principle of success. Before finding failure scenarios, it is important to know what the route of success or "as-planned" scenario is.

This will tell us how the operation, event, and so on (scenario) goes when everything is going according to plan. A useful thought can be to imagine the success scenario, S_0, as a trajectory in the "state space" of the system. The figure below illustrates a success scenario, where S_0 is seen as a trajectory in the state space of the system.

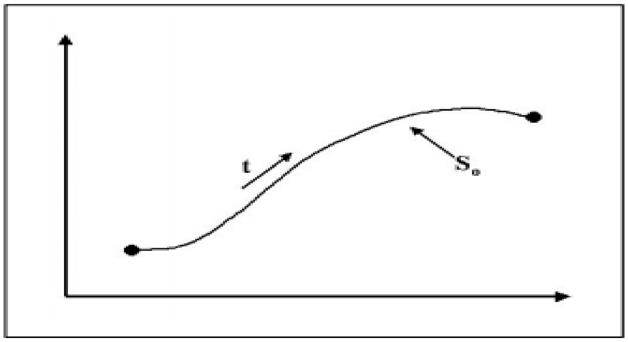

FIGURE 4: SUCCESS SCENARIO, S_0, SEEN AS A TRAJECTORY IN THE STATE SPACE OF SYSTEM

3.3.2 THE PRINCIPLE OF INITIATION

If the path of success doesn't go as planned, a failure scenario, S_1, would have to have a departure from the successful plan. At this stage, something happens that results in the departure, and this is called the "Initiating Event" (IE). An IE can be both internal and external. The below figure illustrates the departure from the successful plan with an IE.

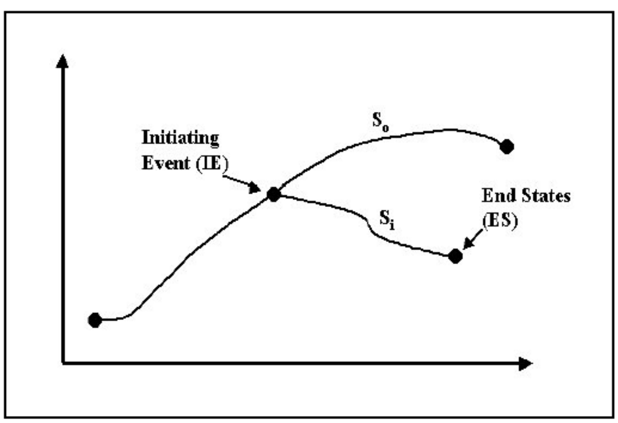

FIGURE 5: THE RISK SCENARIO S_1 AS A DEPARTURE FROM S_0

3.3.3 THE PRINCIPLE OF EMANATION

From each individual initiating event, a handful of possible scenarios emerge. This can be called a scenario tree, and each path represents one type of scenario that occurs depending on the initiating event. Each new path will continue until it reaches the "end" of that scenario, and we call this the "End State" (ES). The ES can be either a positive result or a negative result. If it is positive, or what Kaplan would call benign, we would call the end state BES. Harmful end states on the other hand will be called HES. The figure below illustrates new paths developed from IE.

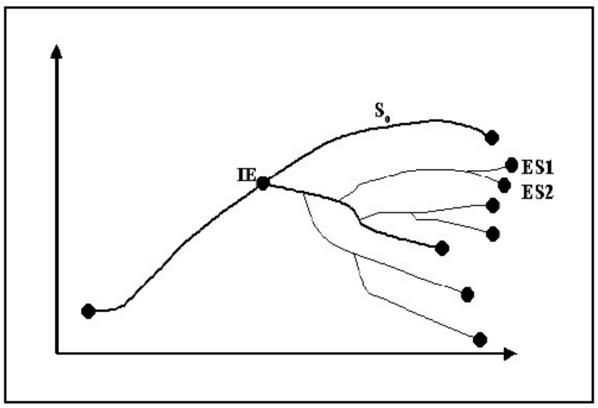

FIGURE 6: SCENARIO TREE WHERE NEW PATHS EMERGES FROM THE IE

3.3.4 THE PRINCIPLE OF UNENDING CAUSE-EFFECT

This principle is about one end state being another scenarios initiating event. For instance, the broken valve that is our initiating event is the end state for the producer who made it.

3.3.5 THE PRINCIPLE OF SUBDIVISION

Every initiating event can be divided into subcategories. An example is; the initiating event in a drilling situation "losses" can be divided into seepage losses, severe losses, wellbore breathing and so on.

3.3.6 THE PINCH POINT PRINCIPLE

The pinch point principle is described by Kaplan as "having the property that once that pinch point is reached, the downstream tree from that point is independent of the upstream path by which the point was reached." Easier said, a pinch point is a middle state, MS, where different IE's are leading to the same middle state scenario. The figure below illustrates the pinch point principle.

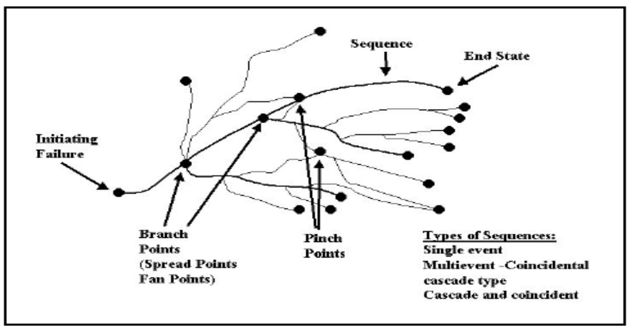

FIGURE 7: SCENARIO TREE WITH PINCH POINTS

3.3.7 THE PRINCIPLE OF FAULT AND EVENT TREES

An end state may have different scenarios leading to it, and also includes different altered initiating events. A particular harmful end state will as a result become a scenario tree, as shown in the figure below. We also call this a fault/event tree.

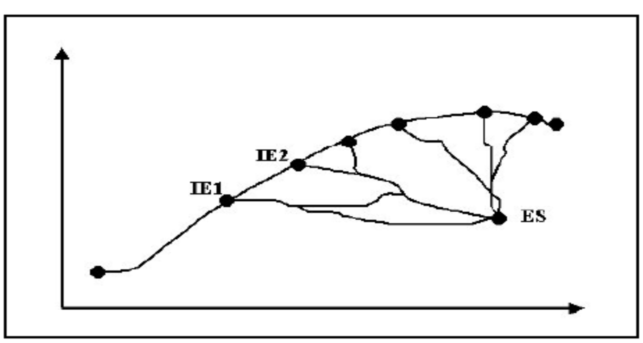

FIGURE 8: AN INCOMING SCENARIO TREE MADE OUT OF DIFFERENT IE'S

3.3.8 THE PRINCIPLE OF RESOURCES

There are a lot of resources that are required for a scenario to occur or not. Resources are hence one of the principles of scenario structuring, as an event may occur whether a resource is present or not. Resources like substances, field, configuration, time and space are taken into account. It is stated that "*If all the resources necessary for an IE are present in a situation, then that event will occur; and conversely, if at least one of the necessary resources is not present, then that event will not occur.*" (Kaplan, Zlotin et al. 1999).

3.4 THE CONCEPT OF BLACK SWAN TYPE OF EVENT

Donald Rumsfield, a former United State Secretary of Defense, introduced the term "unknown unknowns" in 2002, when he spoke at a press briefing regarding the Iraq war. He said the following words:

"*There are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know*" (Aven 2013)

It is not the first time this wording has been used. According to Aven (2013) it has also been used in the matter of climate change. However, we might also say that it is inspired by the Johari Window, a model that works as an information processing tool. The model was created in 1955 by Joseph Luft and Harrington Ingham, and has four different windows of information (Luft 2004):

1. Open or Free Area (Known)
2. Blind Area (Known Unknown)
3. Hidden Area (Unknown Knowns)
4. Unknown Area (Unknown Unknowns)

A black swan is, according to Aven (2013) "*a surprising, extreme event in situations with large uncertainties*" or "*a surprising extreme event relative to the expected occurrence rate*". The well-known risk analyst Taleb (2007) states that a black swan is an improbable event with three attributes. Firstly, a black swan is an outlier – nothing in the past can judge the expectations for the event to happen. Secondly, the event comes with an extreme impact – the impact can be both negative and positive. Thirdly, despite being an outsider, human nature tends to explain and understand why it firstly occurred. Thinking back in time, it is easy to categorize events as black swans when a black swan is defined as above. For instance, the terrorist attack in New York 9/11, this event came as a surprise on America and the world in general. On the level the attack was executed, no similar event that has ever been executed before is comparable. The same regards the tsunami that destroyed the Fukushima Daiichi nuclear plant in Japan in 2011. This event, on the other hand, was caused by a natural disaster. However, the likelihood for it to happen was considered negligible (Aven 2014).

3.4.1 CATEGORIES OF BLACK SWAN

Aven (2013) defines a black swan as an event that is surprising in situations with large uncertainties. But whether an event is surprising or not depends on the person judging it. Aven & Krohn (2014) uses this definition and introduces three different types of black swan events:

1. Unknown Unknowns – events that we don't know that we don't know. Events that are completely unknown for the scientific environment
2. Unknown knowns – events that are known to some, but not the ones who executed the risk analysis
3. Knowns – Events that are known, but seen as too negligible for them to happen

The first category of black swan represents extreme surprises that are beyond our imagination. This can for instance be a new type of virus never seen before.

The second category represents what Aven (2014) articulates as "*events that are not captured by the relevant risk assessment, either because we do not know them, or we have not made a sufficiently thorough consideration.*" It is further stated that if a more thorough analysis had been conducted; the events could have been treated accordingly.

The third and last category of the black swan represents the events where there exist thoughts of a surprising event to occur, however, the event is seen as negligible and hence is disregarded. An example of this is the Fukushima nuclear plant catastrophe that happened in 2011, mentioned in section 3.4.

The figure below illustrates the black swan categories:

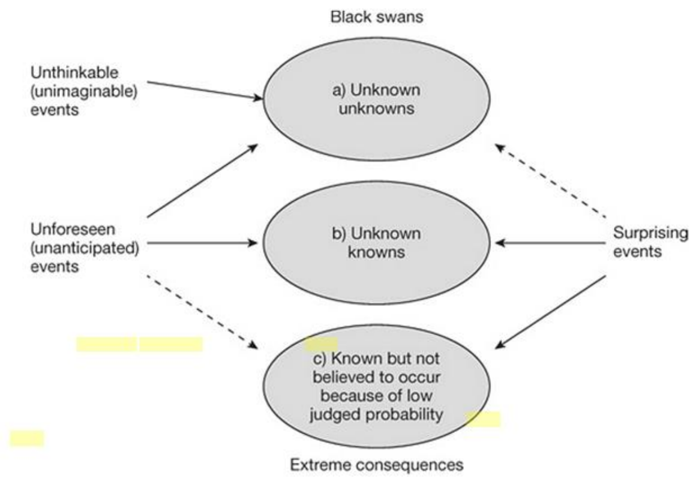

FIGURE 9: SCHEMATIC ILLUSTRATION OF BLACK SWANS (AVEN 2014B)

3.5 TRIZ – THEORY OF INVENTIVE PROBLEM SOLVING

There comes a time where projects reach a point where the analysis is done and the next step is unclear. The project team must at this point start to think creatively and figure out what the next step can be. Problem solving methods such as brainstorming, trial & error and other methods are not always the best as they are described as psychologically based with unpredictable result (Barry, Domb et al. 1996). Brainstorming is also limited to the knowledge of the members of the crew.

In 1946, the Soviet inventor, engineer and scientist Genrich Altshuller developed the tool "Theory of Inventive Problem Solving" (TRIZ) which is the name for the Russian acronym TRIZ. Altshuller worked in the "Invention Inspection" department in the Soviet Navy and his job was to help with the initiation of the invention proposals and prepare applications to the patent office. Altshuller analyzed millions of patents from different fields and discovered the patterns that can predict breakthrough solutions to many kinds of problems (Wikipedia). After studying 50 000 patents Altshuller found 40 concepts that he found as "clever" that could offer solution to contradictions. These 40 are today known as the 40 Inventive Principles (Gadd 2011).

There is no doubt that TRIZ is a very comprehensive and intricate tool with a wide variety of sub-tools and techniques. What TRIZ is today is a result of research that has been conducted by a number of organizations over decades. For newcomers of TRIZ, the richness and complexity of TRIZ may seem quite overwhelming. According to Domb (1997) it is more helpful if beginners start with a simplified form of ARIZ. A roadmap for a simplified version of TRIZ is developed and is shown below.

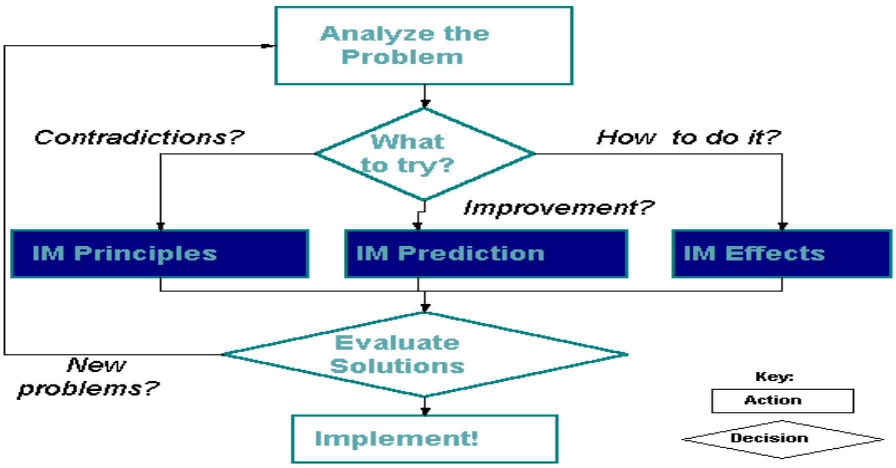

FIGURE 10 SIMPLIFIED TRIZ

The box “analyze the problem” represents three steps;

1. State the Ideal Final Result
2. Perform Functional Analysis and Trimming
3. Find the zones of conflict of the problem

The first step, state the ideal final result, is where you start the whole TRIZ process. You have a problem you want to solve, but first you have to find out how you want your result to end in the most ideal way. Gadd (2011) calls it the golden rule of TRIZ and introduces the following equation for improved ideality:

$$\text{Ideality} = \frac{\text{All Benefits (Primary + Secondary Benefits i.e. all outputs we want)}}{\text{Costs (all inputs) + Harms (all outputs we don't want)}}$$

FIGURE 11 GOLDEN RULE OF TRIZ: HOW TO ACHIEVE IDEALITY (GADD,2011)

where the overall ideality will be to achieve more for less cost with less harm. According to Gadd (2011), the whole TRIZ process includes nine different tools, which she calls the TRIZ toolset;

- Contradiction matrix
- 8 Trends of Evolution

- Effects
- Thinking in time and scale
- Ideal – ideality, the ideal outcome, ideal solution, ideal system and ideal resources
- Resources and Trimming
- Function Analysis and Substance Field Analysis
- Standard solutions
- Creativity Triggers

When it comes to what type of tools that are for importance of TRIZ, it all depends on the author. However, according to Bernerd Dull (2006) we can minimize the above list of tools to the following list below, and these tools will be highlighted:

- Contradiction Analysis
- Ideality
- ARIZ – Algorithm for Inventive Problem Solving
- Patterns of Evolution
- AFD – Anticipatory Failure Determination

The explanation of the five tools below is based on (Apte), (Bernerd Dull 2006) and (Gadd 2011)

Contradiction Analysis

This tool is the most common for TRIZ analysis and is related to the 40 Inventive Principles. Altshuller said that contradiction appears when trying to improve one property and another property weakens. With his research, Altshuller found out that there are only 39 features that can improve or degrade. Features like weight, length, reliability, power, complexity and productivity, to mention a few. He later found out that there were 40 inventive principles that could solve the contradictions - contradiction between the 39 features. The 40 Inventive Principles could be asymmetry, dynamics, feedback, self-service and homogeneity to name a few. If one has a problem; one would find the contradiction to the problem and then see if it fits in the format of the 40 Inventive Principles. Altshuller put the contradictions and the resolution to the contradiction into a contradiction matrix.

Ideality

As mentioned earlier, ideality is about finding the best solution where cost and efficiency are key elements. Ideality reflects the maximum usage of existing resources. Ideality further reflects a more reliable, simple and efficient system. Examples of functions to increase ideality are given below

- Increase amount of functions in system
- Utilize external and internal resources
- Transfer functions to a “super-system”

ARIZ

ARIZ is the main analytical tool of TRIZ, and is a systematic way to identify solutions to complex problems. Altshuller put up a step-by-step procedure for users of TRIZ to understand how to solve problems that contained contradictions.

1. Identify the problem
2. Make Su-Field Models
3. Formulate an Ideal Final Result (IFR)
4. Make a list of available resources
5. Look into databases and find analogous solutions
6. Resolve technical or physical contradictions
7. Use the Su-Field model and generate solutions
8. Implement solutions using resources
9. Analyze the modified system to verify no drawbacks

Patterns of Evolution

Altshuller meant that “every system evolves towards increasing ideality”. When doing his research for the contradiction matrix, he found that every technical system followed objective laws, and weren’t random as he first thought. He later introduced that the evolution of any type of system would work with 8 specific patterns. Altshuller eighth patterns of technical system evolution is given below

1. Life cycle of birth, growth and death
2. Trend of increasing ideality
3. Uneven development of sub-system resulting in contradictions
4. Matching parts and later mismatch them
5. Increase complexity through integration
6. Go from macro-system to micro-system
7. Dynamism and controllability
8. Decreasing human involvement

AFD

Anticipatory Failure Determination, AFD, is one of the newer tools introduced to TRIZ. AFD is a tool for identifying and eliminating system failure before they occur. Questions like "How can we make this system fail" are asked.

As TRIZ is a highly comprehensive and intricate tool, and the writing of this thesis is only ongoing for 5 months, a deeper understanding of TRIZ will not be given. However, one of the basic tools for TRIZ, Anticipatory Failure Determination (AFD), will be further reviewed and later used as a foundation for the development of the model in chapter 4.

3.5.1 ANTICIPATORY FAILURE DETERMINATION - AFD

Anticipatory Failure Determination is a tool used in TRIZ, and is based on the concept of Subversion Analysis. Subversion Analysis is a basic technique that is using TRIZ in reverse. By using TRIZ in reverse we find ways for design and processes to fail, or to subvert the basic purpose of the design or process. The purpose is that if one has knowledge of how to subvert the design or process, it is known how to make the design/process better and failures will as a result not occur (Ungvari 1999). The idea is to invent, create and cause failures/risks. AFD can be used when there exist little or poor information of failures that have occurred in a system, or a failure that might occur in a system. When it comes to unknown risks, there exists little or poor information on the negative effects, or why dangerous or harmful failures occurs. Without adequate information, one can hardly identify the root causes of the failures and the unknown risks. The process of AFD is a rather comprehensive process, but the core idea has the following steps (IdeationInternational 2012):

1. **INVERT THE PROBLEM**

Instead of asking "*Why did the failure happen?*" We would rather ask "*How can I make the failure happen?*"

The key word in the first step is "how". We would like to find out how problems can occur, and hence ask *how* this problem can occur in the future. This goes back to TRIZ and inventiveness as a failure problem/risk has become an inventive problem/risk.

2. **IDENTIFY FAILURE HYPOTHESIS**

In this step we would have to find a method where the failure/risk can be deliberately produced.

3. **UTILIZE RESOURCES**

Find out if all the factors necessary to realize the hypothesis are available, or if they can arise from what is already available. The following questions can be asked (IdeationInternational 2012):

- Are the required **substances** and materials present?
- Is the necessary **energy** available or producible?
- Is there **time** in which the failure/risk can "mechanize"?
- Is the **space** available for the failure to take place

Further, Kaplan (1997) gives a fully explanation and review of the AFD process and states that AFD has four different aspects that are of importance:

1. AFD asks a different question
2. The AFD templates (AFD-1 and AFD-2)
3. The AFD checklist (knowledge base)
4. The TRIZ analytical (inventive) methods

The four aspects will be given an explanation below.

3.5.1.1 ASK A DIFFERENT QUESTION

As mentioned above, questions like "how can we make the operation go wrong?" are asked in order to invert the scenario into an inventive problem. Denial is a vulnerable act for human beings, and it is extremely easy for every human to say that "that will never happen" or "it has never happened before". Having this mindset makes it hard to predict and "make up" scenarios. If one oppose the denial phenomenon it makes the process of identifying scenarios easier. According to Kaplan, there is reason to think that inverted questions are useful when opposing denial. Asking the question, which is done in a QRA, "What can go wrong with the operation?" the mindset is put in a defensive situation. However, if inverted questions are asked, the mind is set in an offensive situation where creative intelligence arises.

3.5.1.2 AFD TEMPLATES

AFD is divided into two different templates, 1 and 2, that work as a guide on how to work through the AFD processes. AFD-1 is mostly used for failure analysis which includes determining the reasons why failures occurred. AFD-2, on the other hand, is used for predicting failures that will occur in the future. In this thesis, the AFD-2 template will be used for prediction of possible failures, and AFD-1 will not be further addressed. However, it must be emphasized that AFD-1 also can be used as failure prediction, as once an ES, or MS, has been encountered, AFD-1 can be used to find out how these states were encountered in the first place.

The process of AFD-2 is explained in section 3.5.2.

3.5.1.3 THE AFD CHECKLIST (KNOWLEDGE BASE)

It can be hard to identify something that can go wrong with a system if it to most people appears to be a good functioning system. It is here the AFD checklists, or the Knowledge base as it is also called, comes into the picture. Figure 4 illustrates the trajectory of a system/operation where all phases are going according to plan. A good way of understanding these checklists is to look at this figure and find out where the vulnerability is greatest.

Every operation, or at least almost every operation, is time dependent. The first two checklists are based on time (Kaplan, Zlotin et al. 1999):

<u>Time-oriented checklists</u>

Checklist 3: Typical stages in the life circle of a technical system

- 3.1 Manufacturing
- 3.2 Testing
- 3.3 Packaging
- 3.4 Transportation
- 3.5 Sales and Purchasing
- 3.6 Installation
- 3.7 Maintenance
- 3.8 Repair
- 3.9 Disassembly and Salvaging

Checklist 5: Typical dangerous periods in a systems functioning

5.1 Periods of departure of usual routine
5.2 Periods of stressful change
5.3 Periods of change in personnel
5.4 Periods of high stress in an workers personal life
5.5 Periods when tests and maintenance occur
5.6 Periods of crowding and vulnerability to panic
5.7 Periods when security is weak.

There are also sub checklists to some of the bullet points. In addition to time-based checklist, there are also the following types of checklist "Space-oriented", "Types of failure", "Failure-intensifying" and "others" checklists:

<u>Space-oriented checklists</u>

We can ask, after finding the time where we are most vulnerable, in what regions we are most vulnerable.

Checklist 4: Typical weak and dangerous zones

4.1 Flow concentration
4.2 Zone subjected to the action of high intensity fields
4.3 Conflict zones
4.4 "Bad history" zones
4.5 Zones containing junctions of different systems
4.6 Multi-function zones
4.7 Tool-workpiece contact zones
4.8 Zone of concentrated

<u>Type of Failure checklists</u>

After finding the regions where a failure can occur, we can ask what type of failure to invent. The following checklist is for this purpose:

Checklist 2: Typical Harmful Impacts

2.1 Mechanical
2.2 Thermal
2.3 Chemical
2.4 Electrical
2.5 Magnetic
2.6 Biological
2.7 Electromagnetic

2.8 Information
2.9 Psychological/emotional

Further we have;

- Checklist 1: Typical functional failures
- Checklist 6: Typical sources of high danger
- Checklist 7: Typical disturbances of flow
- Checklist 8: Typical resources capable of producing harmful impacts
- Checklist 9: Patterns of typical failures scenarios (including human errors)
- Checklist 10: Methods of intensifying failures
- Checklist 11: Ways of masking or hiding the failure

3.5.1.4 THE TRIZ ANALYTIC METHODS

The TRIZ method has been discussed in section 3.5. A more thorough explanation of the different tools of TRIZ will not be given here, but it should be emphasized that the tools presented as the TRIZ tools can be understood as examples of the "principle of solution by abstraction" (Kaplan, Zlotin et al. 1999).

3.5.2 ANTICIPATORY FAILURE PREDICTION 2 – AFD-2

As mentioned in section 3.5.1.2, AFD consist of two processes; AFD-1 and AFD-2. AFD-1, Anticipatory failure determination, will not be given any further attention. The process of AFD-2, Anticipatory Failure Prediction, is described in the points below, and is based on the AFD-2 template in (Kaplan, Zlotin et al. 1999).

1. **FORMULATION OF THE ORIGINAL PROBLEM**

Here is the original situation described with the undesired events. One can use the following wording;

"There is a system called *[name of system]* ***for*** *[describe purpose of system].* ***We wish to find all possible undesired effects or failures that can occur within, or as result of, this system, and to identify the ways in which these undesired phenomena can occur"***

2. IDENTIFY THE SUCCESS SCENARIO

An overview is given with the successful operations/phases and their result. A table like the following can be made;

Successful operations / phases	Result

3. FORMULATE THE INVERTED PROBLEM

The inverted problem is first invented in step three, and we can use the following wording;

"There is a system called** [name of system] **for** [describe]. **It is necessary to produce all possible undesired effects or failures that can occur within, or as a result of, this system".

The figure below illustrates the mode of thought when having a normal approach to the dominos versus the AFD approach.

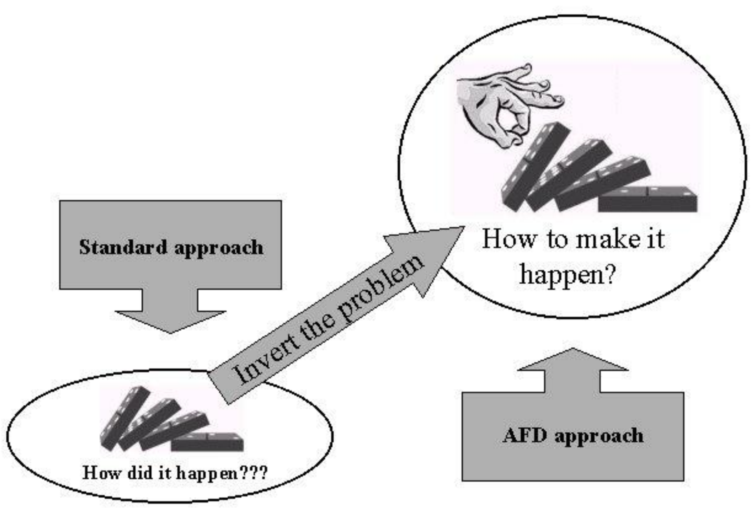

FIGURE 12: INVERTING THE PROBLEM (IDEATIONTRIZ.COM)

4. APPARENT WAYS TO DETORIATE THE SYSTEM FUNCTION

Here one will have to find all initiating events leading to a function failure. One will also have to find the harmful end states that the initiating events end with, and possible risk scenarios. Possible risk scenarios are developed as the middle states, and are states that are between the initiating event and the end state.

To create and invent new possible events we can use the checklists. It can be problematic to invent new events if the system appears "bulletproof". With the use of the checklists, as stressed in section 3.5.1.3, designing new possible events is made easier as it stimulates the brain to think more creatively.

5. IDENTIFICATION OF AVAILABLE RESOURCES

In most cases, resources need to be present for something to occur. It is for instance hard to ignite something without oxygen. In this case, oxygen is the resource required if fuel and heat are already available. If the resources required for some event to happen are not present, the scenario will not occur either. In search of events to happen, we need to find all possible resources that are available and place them in a favorable position. The concept of resources in AFD is based on the following wording;

"For any failure or drawback to occur spontaneously, all the necessary components must be present within the system or its nearby environment. If all those components are present, the failure will necessarily occur."

The below figure illustrates the use of resources in the AFD process:

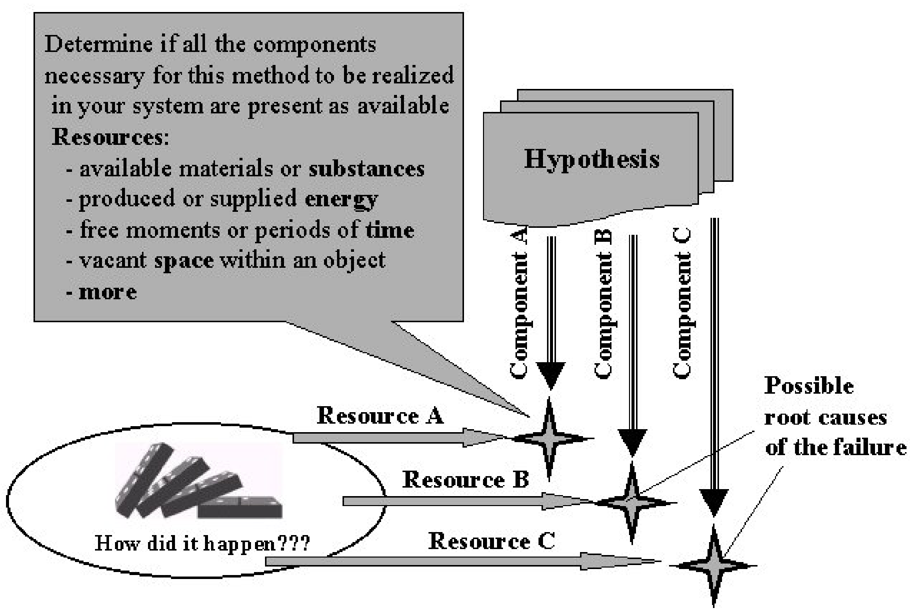

FIGURE 13: UTILIZATION OF RESOURCES (IDEATIONTRIZ.COM)

Effectively, the AFD process will create new resources in addition to the ones already present. An example can be if acid is required for an explosion to occur. The question is then, "*how can we make acid out of the resources we already have?*"

The resources in AFD-2 are the following:

- Substances
- Field
- Space
- Time
- Functional
- Systematic
- Change
- Differential
- Inherent
- Organizational
- Small Failures Disturbances
- Hazardous Elements
- Control Devices
- Protection System

6. UTILIZATION OF THE AFD KNOWLEDGE BASE

The checklists already described in section 3.5.1.3 are used to provide more detail on the scenarios developed from the resources, and to identify additional ones.

The inventive problem is compared to the following checklists:

- Typical Stages of Technological System Life Cycle
- Typical Weak and Dangerous Zones of System
- Typical Functional Failures
- Typical Harmful Impact
- Typical Dangerous Moments in the System Functioning and Evolution
- Typical Sources of High Danger
- Typical Disturbance of Flows of Substance, Energy, and Information
- Typical Resources

These checklists are tied up to the numbered checklist described in chapter 3.5.1.3. The first checklist, "Typical Stages of Technological System Life Cycle" is tied up to checklist number 3. "Typical Weak and Dangerous Zones of System" and "Typical Harmful Effects" have the following sub-list;

1. Mechanical
2. Thermal
3. Chemical

4. Electrical
5. Magnetic
6. Biological
7. Electromagnetic
8. Information
9. Psychological

Further, “Typical Sources of High Danger” classifies the possibility for creating failures with high impact. “Typical Functional Failures” is contributing to find failures on functions like “system”, “component” or “device”. For the “Disturbance of flow checklist” there are suggested multiple ways to interface flows in the system.

All checklists are not listed here, as they are not available without the AFD software.

7. INVENTION OF NEW SOLUTIONS

In step 7, ARIZ – An algorithm for inventive problem solving is being used. ARIZ is briefly explained in of chapter 3.5, however ARIZ for AFD has the following steps mentioned below that are to be followed.

<u>Step 1</u>

- Describe the problem or obstacles.

What kind of failures do we want to cause to initiate a system/operational fail?

<u>Step 2</u>

- Describe ideal conditions that must be present to realize harmful effects

<u>Step 3</u>

- Do we know how to provide ideal conditions?

The Innovation Guide is a very useful tool for this step, however it is only available with the AFD software.

<u>Step 4</u>

- Do we know of any limitations that restrict us from having ideal conditions? Describe.
- Contradictions – are there any contradictions to produce harmful effects that are not achievable for any reasons?

8. INTENSIFICATION AND MASKING HARMFUL EFFECTS

In step 8 we try to intensify the harmful effects we have discovered so far. Are there ways to amplify the harmful effects? In that case, describe them.

9. ANALYSIS OF REVEALED HARMFUL EFFECTS

The analysis of the revealed harmful effects can be presented with outgoing event trees and diagrams that categorize and label the scenarios.

10. PREVENTION / ELIMINATION OF HARMFUL EFFECTS

Present ways to prevent the harmful effects. The software is, as on other steps, used here as well. However, with imagination one can manage without. Some of the different ways to eliminate harmful effects described by (IdeationInternational 2012);

- Eliminate the cause of failure
- Remove the source of harm or change properties
- Modify the harmful effect
- Increase the systems resistance to the harmful effect
- Modify and/or substitute the object that is effected
- Counteract the harmful effects

It is only imagination that can stop you from eliminating the harmful effects; however the points above come in good hand when doing the analysis.

The ten different steps in AFD have now been presented. We will use these steps as far as possible when performing the analysis for subsea PnA in chapter 5.

4. SUGGESTION OF NEW MODEL BASED ON ANTICIPATORY FAILURE PREDICTION

As described in chapter 3.1, we have events and consequences. Figure 14 below illustrates a model with the general risk picture; where events lead to consequences. For every scenario we have events and their consequences. When there is a change or a modification to that scenario, new events and consequences might occur. As a result, the events and consequences we had prior to the modification become "old" events and consequences, and the ones after the modification become the "new" events and consequences. In addition, the figure illustrates that new events come under the category of the black swan type of events. The four different steps are illustrating the flow of the model, and will be described later.

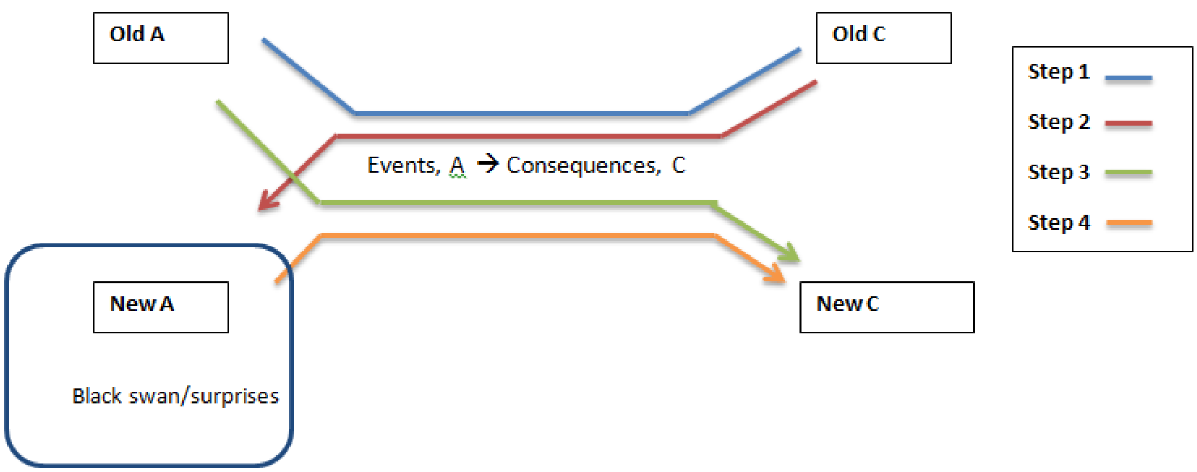

FIGURE 14: THE MODEL WITH OLD AND NEW EVENTS AND CONSEQUENCES

Seeing that we are using AFD for the analysis, and we know from scenario analysis in chapter 3.3 that AFD is using IE's as events and ES's as consequences, a more applicable model of the "general" one above is introduced below. The model expresses the same; just that the notations of IE's and ES's have been replaced. The idea behind the model is that "old" end states, ES's, will be used when inventing new questions as in chapter 3.5.1.1. As illustrated in the figure below, there are old and new IE's. The old IE's and the old ES's are the ones we already have from a known HAZID, the new ones on the other hand, are IE's and ES's we are going to invent from the old ES's later in this chapter. Figure 15 further illustrates that new IE's can, under some circumstances, occur under the category of a black swan.

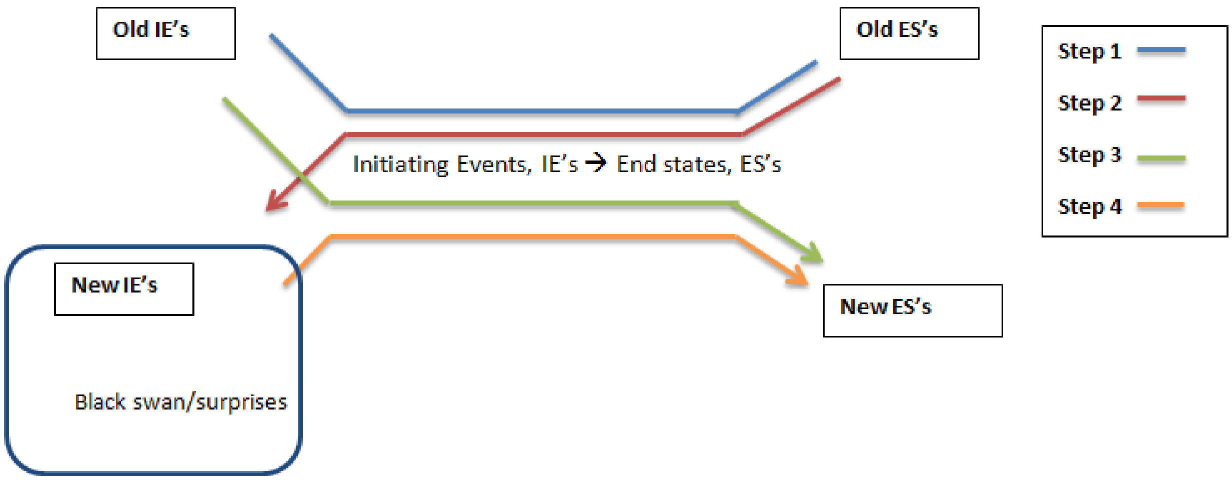

FIGURE 15: THE MODEL WITH OLD AND NEW IE'S AND ES'S

The methodology for this thesis will be based on Figure 15 above, and is illustrated by the different color coded steps. The first step, the blue line, will be to verify that old ES's are relevant, and go from "Old ES" back to "Old IE" to see how the end states ended up the way they did. The second step, the red arrow, will be to take the old ES's and use the AFD process to create new IE's. The third step, the green arrow, will be to go from relevant "old" IE's and see whether these give any "new" ES's. The last step, the orange arrow, will be to go from the "new" IE's and create "new" ES's. A stepwise procedure will be as the following:

1. Blue line: Verify that "old" ES's and "old" IE's are relevant to new activity
2. Red arrow: Go from "old" ES's and create "new" IE's
3. Green arrow: Go from relevant "old" IE's to and create "new" ES's
4. Orange arrow: Go from "New" IE's and create "new" ES's

4.1 EVERYDAY EXAMPLE OF MODEL

To try to make the above model easier to understand, an everyday example is given below;

The bus has been used as transport to work for a long time, but there has been a tendency of coming late to work. Because of this it is now decided to buy a car. We can say that we have the two activities "taking the bus to work" and "driving to work". The old ES for both activities we will look at is "coming late to work". The figure below illustrates the situation:

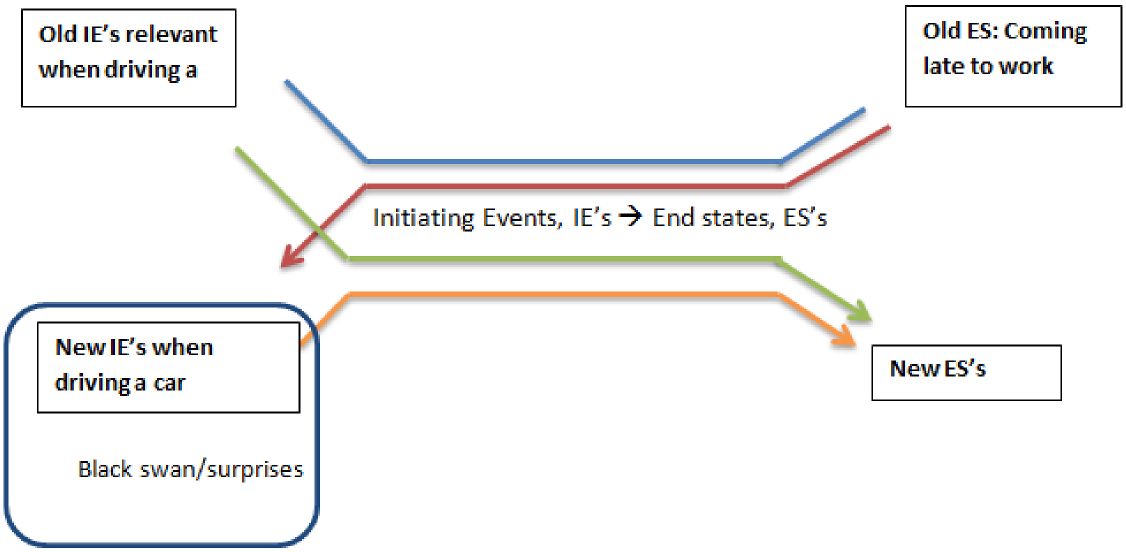

FIGURE 16: THE BUS/CAR SITUATION WHERE ES IS "COMING LATE TO WORK"

We will used the developed model and see if we can create some new IE's to the ES "coming late to work" by driving a car. We are following the four step procedure to identify new IE's and ES's for the new activity, driving a car, and the first step is:

1. **<u>Verify that "old" ES's and IE's are relevant to new activity</u>**

The first step will be to go from old ES to old IE. In other words; creating reasons why we come late to work by taking the bus, and see if they are relevant for the new activity. The one ES we will look at in this example is the following:

- OLD_{ES1}: Coming late to work

We know different reasons to why we come late to work as we have been taking the bus for some years:

- OLD_{IE1}: Arriving late to bus stop
- OLD_{IE2}: The bus takes a detour
- OLD_{IE3}: Thunderstorms and heavy rain makes the walk down to bus station a bit less comfortable which results in a delay
- OLD_{IE4}: Traffic accident
- OLD_{IE5}: Bus too full, have to wait for new bus

Out of these five mentioned IE's leading to the ES of coming late to work, it is only traffic accident, OLD_{IE4}, which is relevant for the new activity "driving to work". The other IE's are only applying when taking the bus.

2. Finding "new" initiating events from "old" end states

The next thing is to create new IE's from the old ES. In other words; create reasons why we come late to work by driving a car. We ask the question "How can we arrive late at work when we are driving a car?" Creative thinking provides the following answers:

- NEW_{IE1}: Stuck in traffic (not allowed to use the "public transport line/bus line")
- NEW_{IE2}: Low on gas – need to stop on next gas station to fill up
- NEW_{IE3}: Traffic accident

Out of these three IE's, it is only the first two, NEW_{IE1} and NEW_{IE2}, that applies when driving a car.

3. Finding "new" ES's from "old" IE's

We have now gone backwards from old ES's to new and old IE's. We would also like to go forward from old IE's to new ES's. We found five IE's in step.1 resulting in "coming late to work", however only one of these were applicable for "driving a car". The IE's we found were:

- OLD_{IE4}: Traffic accident

The question will be: "what end states can we cause with a traffic accident when driving a car based on OLD_{IE4}?" We create the following new ES's:

- NEW_{ES1}: Damage to car
- NEW_{ES2}: Personal injury
- NEW_{ES3}: Loss of life

NEW_{ES2} and NEW_{ES3} are also possible when taking the bus, but that is not what we asked for. This step was only looking for new ES from old IE's.

4. Finding "new" ES's from "new" IE's

The last step is to find new ES's from the new IE's we created in step. 2. We can conclude that NEW_{IE1} and NEW_{IE2} are resulting in "coming late to work", hence no new ES's. We can further conclude that NEW_{IE3} can result in in the same ES's as in step.3 when finding new ES's from old IE's.

The following figure sums up the scenario we have, with old IE that are relevant for the new activity and new IE's, and new ES's:

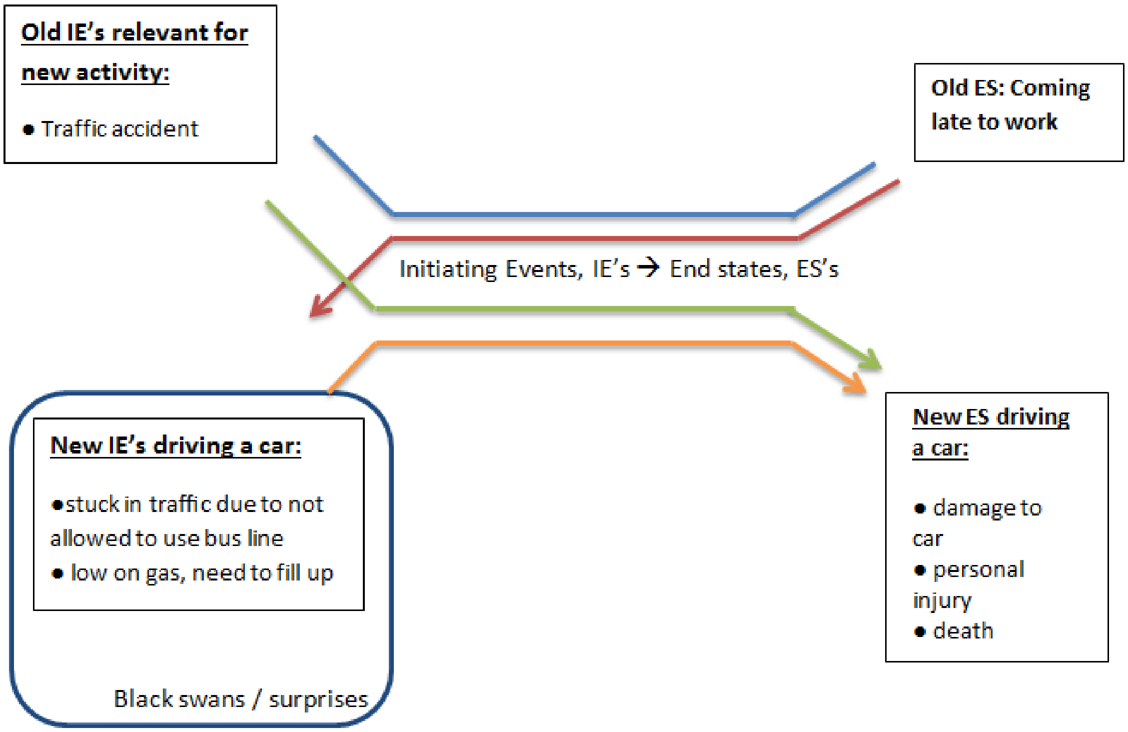

FIGURE 17: SUMS UP BUS/CAR SCENARIO

This is also summed up in the following two tables:

OLD ES → OLD AND NEW IE's		
	Taking bus	Driving car
Old and new IE's		
Arrive late to bus stop	x	
Detour	x	
Heavy weather	x	
Traffic accident	x	x
Bus too full - wait	x	
Stuck due to not allowed to use bus line		x
Low on gas - have to stop for gas		x

TABLE 2: SUMMARIZE OLD AND NEW IE'S

OLD AND NEW IE's → NEW ES's	
	Driving a car
New ES	
Damage to car	x
Personal injury	x
Loss of life	x

TABLE 3: SUMMARIZED NEW ES'S

As we can see from table 2 above there are more IE's when taking a bus than driving a car that are leading to the ES's "coming late to work". However, as seen in table 3 there is one more ES related to driving a car than taking the bus. We can say that there are more end states when driving a car, but there are more events leading to coming late to work when taking the bus.

In the bus/car example, AFD is not used thoroughly to determine the new IE or ES as it is a very basic example. With that said the core idea still remains the same; having an ES and use reverse thinking to find IE's.

5. APPLICATION OF MODEL IN SUBSEA PNA

As subsea PnA has never been performed before on the NCS, it is highly interesting to use a method like AFD to try to invent failures. The plugging of all the subsea wells will most likely be facing some scenarios that are not included in the risk assessment, and those will be scenarios that are immensely difficult to foresee prior to plugging. As stressed before in this thesis, finding scenarios that one never has encountered before is border line impossible. With that said we will apply our model to subsea PnA and try to invent possible failures that can occur when performing subsea PnA. The HAZID presented in chapter 2.2.2 and appendix A will be the foundation for the analysis.

In a subsea PnA project, an overall figure for the situation will be as the following figure illustrates:

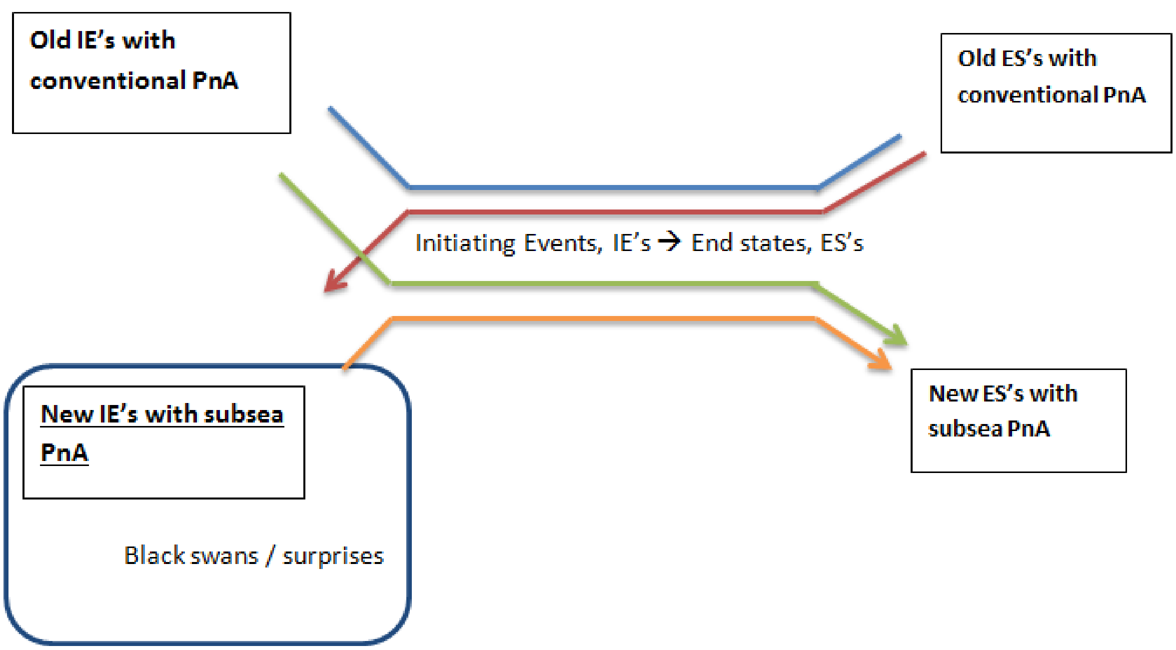

FIGURE 18: OVERALL MODEL FOR THE ANALYSIS FOR SUBSEA PNA

5.1 STEP 1. FINDING OLD IE'S FROM OLD ES'S

We are referring to Figure 15 and step no. 1 in the stepwise procedure, and the first step will be to verify that old ES's are relevant, and to find old relevant IE's. Some ES's have been selected from the Camelot PnA HAZID extract found in appendix A. The following scenarios and ES's are relevant for subsea PnA, and are shown in the table below:

Scenario	Old ES
Chemicals handling	ES1: Exposure to people and environment
Explosive Handling	ES2: Explosion on boat
Obtain well isolations	ES3: Poor well isolations
Run in hole with tools and pipe	ES4: Stuck tools and pipe
Cementing operations	ES5: Poor cement job
Emergency shutdown (ESD) usage	ES6: ESD does not work when needed

TABLE 4: THE TABLE SHOWS THE END STATES ACCORDING TO THE CAMELOT PNA PROJECT

We ask questions like the following to get answers when going from old ES to old IE's;

- How were people and environment exposed to chemicals during the conventional PnA?
- What made an explosion occur during conventional PnA?
- How did we fail to obtain well isolations during conventional PnA?
- How did we manage to get stuck tools and pipe during conventional PnA?
- What caused a poor cement job during conventional PnA?
- How did the ESD system fail during conventional PnA?

The table below lists different initiating events leading to the end states given above in table 4. There is no doubt that there are many initiating events leading to poor end states. The IE's below is only some of them, and is limited to the writer's knowledge of subsea PnA.

Scenario	Old ES	**Old IE's** (how it was performed under conventional PnA)
Chemicals handling	ES1 - Exposure to people and environment	**IE1a**: Exposure to people when mixing fluids. **IE1b**: Exposure to environment with leakages when transferring fluids, riser rupture
Explosive handling	ES2 - Explosion on rig	**IE2a:** Blowout from kick **IE2b**: Explosives from tools
Obtain well isolations	ES3 - Poor well isolations	**IE3a**: Perform a poor cement job **IE3b**: Inadequate logging of casing etc.

Run in hole with tools and pipe	ES4 - Stuck tools and pipe	**IE4:** Hydrate plug formation
Cementing operations	ES5 - Poor cement job	**IE5a:** Inadequate pump rate **IE5b**: poor quality of cement **IE5c:** Not sufficient volume of cement **IE5d:** Cement not static for sufficient amount of time
ESD usage	ES6 - ESD not working when needed	**IE1:** Automatic sensors (gas for example) not working or are covered with a sheet **IE2:** Lack of maintenance resulting in fault in electrical chain

TABLE 5: OLD IE'S TO OLD ES

We have now established the first step in the stepwise procedure, and found the old IE's to the old ES's. We verify that all of these are relevant to subsea PnA.

5.2 STEP 2. CREATING NEW IE'S FROM OLD ES'S WITH THE USE OF AFD ANALYSIS

The second step in the four step procedure is creating new IE's from old ES's. The AFD-2 template will be used to invent failures that can go wrong for the subsea PnA operation. The AFD-2 template will not be used consistently for every point, and some points are left out. Nevertheless, the purpose of the analysis is to use the idea behind the AFD-2 template, and the start of the analysis will follow the steps of the template.

1. **Formulate the original problem**

We have a known situation and we want to formulate the problem, the following wording is used;

"We have an operation called ***subsea PnA*** *for* ***plugging and abandonment of subsea wells****. We wish to find all possible undesired effects or failures that can occur within, or as a result, to this operation, and to identify the ways in which these undesired phenomena occur. "*

2. **Identification of the success scenarios, S_0**

If all sequenced operations in the subsea PnA operation go according to what is planned, the following success scenarios will occur;

Successful operations / phases	Result
Chemicals handling	No injury to personnel or environment while handling chemicals
Explosive handling	No injury to personnel prior, during and after handling explosives
Obtain well isolations	Well fully isolated
Run in hole with tools in well	No stuck pipes or tools
Cementing operations	No injury to personnel. No dust, blockages of lines, potential health hazards or potential cement ingress to HVAC system. No spill.
ESD – Emergency shutdown usage	ESD works when needed

TABLE 6: THE SHOWS AN OVERVIEW OF THE SUCCESS SCENARIOS AND THEIR RESULT

3. **Formulate the inverted problem**

The following wording is used to articulate that the problem is inverted;

*"We have an operation called **subsea PnA** for **plugging and abandonment of subsea wells**. It is necessary to produce all possible undesired effects or failures that can occur within, or as a result of, this operation"*

4. **Apparent ways to deteriorate the system function**

In this step one wants to find all possible initiating events that can lead to failure of the operation. The question "how can we make this scenario fail?" is asked for all the scenarios:

- How can we make the chemical handling go wrong?
- How can we make the explosive handling go wrong?
- How can we make the well isolations fail?
- How can we cause tools and pipes to get stuck when they are running in hole?
- How can we make cementing operations go wrong?
- How can we cause the ESD not working?

To try to answer the questions above without help of any kind is difficult; consequently we need to put our mind to creative thinking. The AFD process suggests listing up resources and using the AFD knowledge base to create failures.

5. Identification of available resources

The further we go in doing this analysis, the more complex it gets. All IE's and ES's can be categorized into sub categories, as explained in section 3.3.5. When doing so, the AFD software comes in great help when analyzing and breaking down every step into smaller pieces, but as stressed in the sections on limitations; this software is not within reach. Creative thinking is, as a result of not having the adequate software, the best tool when investigating the resources in this chapter. As the AFD process articulates, ***"For any failure or drawback to occur spontaneously, all the necessary components must be present within the system or its nearby environment. If all those components are present, the failure will necessarily occur."*** We will in this chapter try to find all possible resources that can cause a failure. With that said, trying to find *all* possible resources to end states one has limited technical knowledge of, is a time consuming and rather difficult process. Some resources are hence left out due to knowledge of the technical systems.

The first end state, ES1, is chemical exposure to people and environment. One would think that the scenario "chemicals handling" will be the same in conventional PnA and subsea PnA. However, we are going 30-40 years back in time when drilling mud consisted of diesel and carcinogenic agents such as asbestos. The carcinogenic substance asbestos was prohibited in drilling mud on the NCS from 1980 (Steinsvåg, Moen et al. 2006), however 10 years of active drilling had already taken place on the Norwegian sector. When performing a PnA, one will need to cut and retrieve the casing. Behind the casing we find the old drilling mud. This mud will be pumped up to surface when the cement plugs are set. Table 7 below lists the following resources for ES1 – chemical exposure to personnel and environment.

ES1 - EXPOSURE TO PEOPLE AND ENVIRONMENT		
RESOURCES	**CATEGORY**	**DESCRIPTION**
Substances	**Waste**	•Chemical waste • Evaporation of chemicals when in pit • Waste return from well after PnA
	Raw materials or unfinished products	•Red chemicals • Chemicals used for H_2S prevention
	Substance properties	The returns from old wells can contain: • Carcinogenic agents such as asbestos • Diesel

Field	**Field (energy) from the system**	• Heating and cooling of mud and chemicals cause different properties which can effect negatively
Organizational		• Personnel who don't take precautions regarding hazardous chemicals/liquids. • Untrained personnel • Lack of communication and handovers
Hazardous Elements		• Old mud returns can contain gases not thought of and hazardous evaporation can occur.
Functional	**System that hooks boat to subsea template** **• Riser / hose from boat to subsea template**	•Conventional PnA uses risers made of steel. Subsea PnA use a hose from the boat to the subsea template. Risk of spill increases with the use of hose.

TABLE 7: THE TABLE LISTS THE RESOURCES NEEDED TO CAUSE ES1

As seen in the above table, the resources required causing exposure to personnel and environment are substances, field, organizational and hazardous elements. Functional resources are the resource with most concern, as exposure to environment is at higher risk when a hose is used compared to a conventional riser used on semi submersibles and platforms.

The second end state, ES2, is explosion on the boat. Explosives handling refers mostly to punching tools and other designated tools that are using explosives. There are other sources that can result in an explosion, like blowouts, chemicals and other electrical sources. However, only tools using explosives will only be taken into account in this analysis. Before the plugging of a well can take place, one needs to kill the well with heavy fluid. In order to do this, it is required to punch a hole in the production tubing to establish contact with annulus (annuli between tubing and production casing). This can be done in different ways; but one way is to use electrical energy to detonate explosives when punching hole through tubing. The table below lists the different resources required to cause an explosion on the rig in regards to tools:

ES2 - EXPLOTION ON THE BOAT		
RESOURCES	**CATEGORY**	**DESCRIPTION**
Substances	**Raw materials or unfinished products**	Metal, explosives, chemical explosives,
Field	**Field (energy) from the system / environment**	• Mechanical energy of cutting tool • Electrical energy of the punching tool (punching holes through tubing)
Organizational		• Poor trained personnel • Poor communication between dedicated parties
Time		• If punching tool is run on slickline it can be time based which can result in too early detonation
Functional	**No signal**	• No signal from surface to downhole tool when punching casing

TABLE 8: THE TABLE LISTS RESOURCES NEEDED TO CAUSE ES2

As seen in the above table, the resources needed to cause explosion on the boat is substances, field, organizational, time and functional.

The third end state, ES3, is poor well isolations. 20 – 30 years back the rules and regulations were not as strict as they are today, and data was not collected and stored the same careful way as is done today. Resources required causing poor well isolations and incident related to poor well isolations are listed in the table below:

ES3 - POOR WELL ISOLATION		
RESOURCES	**CATEGORY**	**DESCRIPTION**
Substances	**Raw materials or unfinished products**	steel (casing), brine, cement
	Substances evolved over time	H_2S and CO_2 hydrates
	Substance flow	Leakage through cement plugs
	Substance properties	• Casing wear, • Collapsed casing • Channeling in cement (poor cement job)
Field	**Field (energy) from the system**	• Hydrostatic pressure • Formation pressure • Surge an swab pressure (pressure when tripping in and out)
Organizational		• Poor communication between involved parties
Hazardous Elements	**Information**	• Reduced or little information on older wells. • Not sufficient data from older wells on well integrity

TABLE 9: THE TABLE LISTS THE RESOURCES NEEDED TO CAUSE ES3

As seen from above table substances, field, organizational and hazardous elements are resources that can create failures. A resource to highlight in ES3 is hazardous elements which will in this case be information. Will we know that all well isolations are intact and that well integrity is to trust? It will most likely be a challenging job to get adequate data and information for the oldest wells; thus this is a factor that needs to get extra attention.

The fourth end state, ES4, is stuck pipe and tools. Stuck pipe and tools cost the operators millions of dollars every year in lost rig time, lost production and loss of tools and pipe, together with fishing operations. Stuck pipe can be traced to three different scenarios; human error, failure in equipment and wellbore instability (Enos, Robertson et al. 2013). In the subsea PnA case, we are running in with pipe and tools in a cased hole down to the reservoir, and collapsed and worn casing can be a critical factor for stuck tools and pipe. However, before one can run in hole with cement stinger (a pipe one can cement through) one will need to retrieve all packers and downhole pumps. As mentioned, human errors and equipment failures are the two most common causes for stuck incidents, and the probability of a stuck incident is high. Resources required causing stuck tools and pipe incidents are listed below in the table below

ES4 - Stuck tools and pipe incidents		
RESOURCES	**CATEGORY**	**DESCRIPTION**
Substances	**System Elements**	• Pipe and tools are made of metal, steel, rubber. • Pipe and tools touches drilling mud, formations like sand and clay stone, metal from casing. • Downhole pumps and equipment to be retrieved
	Raw materials or unfinished products	• Stuck in cement when tagging top of cement due to cement has not set completely (not hard cement).
	Substance properties	• Corrosion from metal / casing. • poor casing integrity - stuck in casing (collapsed)
Field	**Field (energy) from the system**	• Hydrostatic pressure when pumping drilling mud down hole causes casing collapse • Mechanical pressure on drill string
Organizational		• Poor trained personnel • Poor communication between dedicated parties
Time		• Stuck pipe when/if circulating out excess cement during cement squeeze operations (if cement has cured)

TABLE 10: THE TABLE LIST RESOURCES NEEDED TO CAUSE ES4

As seen from above table substances, field, organizational and time are resources that can create stuck pipe.

The fifth end state, ES5, is a poor cement job. The most important thing with a plug and abandonment is to seal designated areas of the formation with cement plugs to prevent formation fluids or gases to migrate to surface; hence it is a very critical end state which it is important to create failures related to. Resources required to cause a poor cement job are listed in the table below:

ES5 - POOR CEMENT JOB		
RESOURCES	**CATEGORY**	**DESCRIPTION**
Substances	**Raw materials or unfinished products**	• Not good cement sent out from shore • The drill water that the cement is mixed in contains high content of chlorides (decreased setting time) • Wrong mixing ratio between cement and drill water
	Substance flow	• No movement of cement from boat down to the well if pumps fail
	Substance properties	• Cement does not set (retarder does not work) • Cement has wrong density which causes formation fracking and losses
Field	**Field (energy) from the system / environment**	Hydrostatic pressure in well is not what was expected and cement is too light / heavy
Organizational		• Inexperienced crew and poor communications
Functional	**Boat and subsea equipment**	• Malfunction of mud pumps and subsea pump • Malfunction of volume control system • Heavy underwater currents causing hoses to part

TABLE 11: THE TABLE LISTS RESOURCES NEEDED TO CAUSE ES6

As seen from above table substances, field, organizational and organizational are resources that can cause a poor cement job.

The sixth and last end state, ES6, is the emergency shutdown system. This system is a critical system as it controls the well activities in terms of a possible blowout. Some resources required to cause a failure in the ESD system are listed in the table below:

ES6 – ESD not working		
RESOURCES	**CATEGORY**	**DESCRIPTION**
Field	**Field (energy) from the system**	• Electrical power through umbilicals does not function • Hydraulic power through does not function
Organizational		Personnel unaware how to run the system
Hazardous Elements	Weather	Strong currents can part umbilicals /cause damage to umbilicals

TABLE 12: RESOURCES TO ES6

We have field, organizational and hazardous elements as resources to cause ES6.

6. Utilization of the AFD knowledge base

The next step will be to use the AFD knowledge base to provide more detail on the above scenarios, and if possible, identify new ones. As described in section 3.5.1.3, there are eight checklists that we can use to invent issues. Kaplan, Zlotin et al. (1999) articulates that a good way of understanding these checklists is to go back to Figure 4, where a success scenario is shown in the trajectory of time. If we want something to go wrong, we can look at this trajectory and find those times where the vulnerability is greatest. The main idea with the AFD knowledge base is to go down the list item by item and see whether the different lists can apply for one's own system. However, many of the components in the checklists are not applicable for this analysis, but the checklists will be used to an extent that is applicable for the analysis. To follow up on Figure 15, the below figure demonstrates that we are now going to find IE's from the ES "exposure to people and environment" in subsea PnA, and we are asking the question "how can we cause exposure to people and environment?"

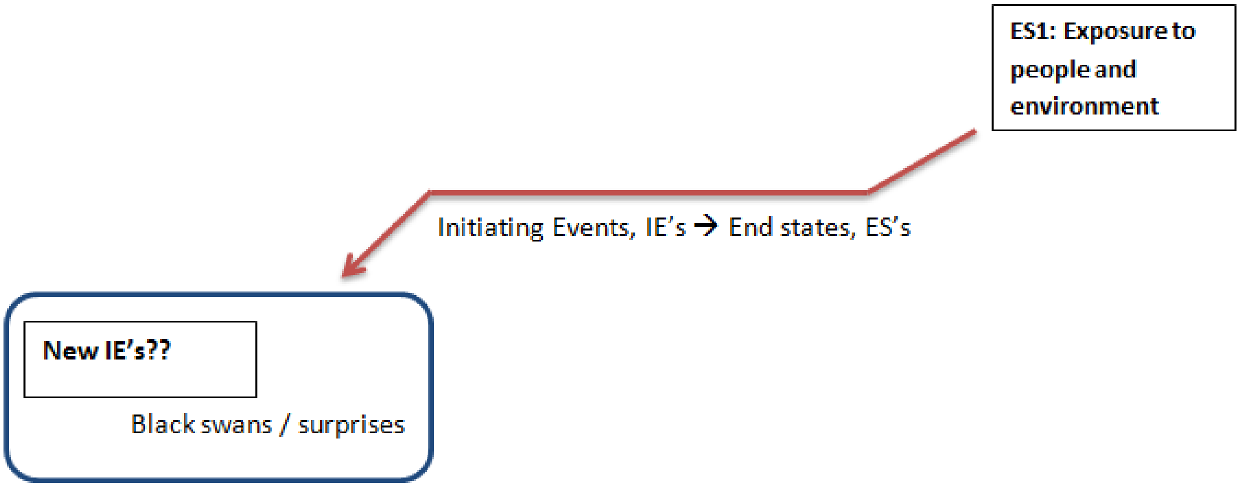

FIGURE 19: FINDING IE'S FOR ES1

We will, as stressed above, use the AFD checklists to a certain extent to create failures. The below table is listing different checklists and the description they have for ES1, chemical exposure to people and environment.

ES1 - chemical exposure to people and environment		
CHECKLIST	**SUBCATEGORY**	**DESCRIPTION**
Typical stages in life cycle of technical system	Manufacturing	Poor quality on chemical from manufacturer can cause higher exposure to people and environment if chemical concentration is not what is expected.
	Packaging	If containers are not packed in a correct manner, people can get chemicals over them when opening container
	Transportation	• Transportation of waste - hazardous gases such as H_2S can arise in waste mud/water. • Transportation of fluids on and off boats can, due to more movement on boats than rigs/platforms, lead to delayed operations. This can, in a worst case scenario, lead to not having the sufficient amount of kill fluid onboard if a kick scenario occurs.
Typical dangerous stages in a system's	Periods of change in personnel	If poor cement / chemicals has arrived boat and this is not communicated to either shore or colleagues

functioning		
Typical Harmful Impacts	Chemical	When mixing chemicals on the boat, the system of mixing can be different to what personnel are used to from conventional rigs/platform and chemical exposure can occur as a result of not knowing how the system works
	Pressure	Putting too much pressure on the riserless mud recovery hose (mud return hose) can cause cracks in the hose leading to spill to sea

TABLE 13: THE TABLE LISTS CHECKLISTS FOR ES1

Table 13 lists different descriptions of operations that can go wrong when it comes to chemicals handling. It must be emphasized that the table includes operations that can go wrong in both conventional PnA and subsea PnA. It is the last point in the table that is the most interesting for subsea PnA – pressure on hose that can cause leak to environment. The other components of the list are not seen as distinctive for subsea PnA. We can say that chemicals handling on the vessel as opposed to on a rig will be similar. However, the possibility of a leakage through a hose is higher than a leakage through metal pipe. The hose will be pressure tested to verify the hose integrity, but this does not guarantee that the hose will not fail during operation. There is also a chance that an error occurs on the subsea pump, fittings on the pump and hose can fail, etc., all which can result in a leak. However, this has no direct relation to "chemicals handling" even though there are IE's that can cause a leak to the environment. We can cause leak to the environment by putting a lot of pressure on the hose, but the leak will not occur due to chemical handling. We can thus conclude that there are no new IE's for chemical handling during subsea PnA.

The next ES is explosive handling, which results in an explosion on the rig. We are now asking the question "how can we cause an explosion on the boat?"

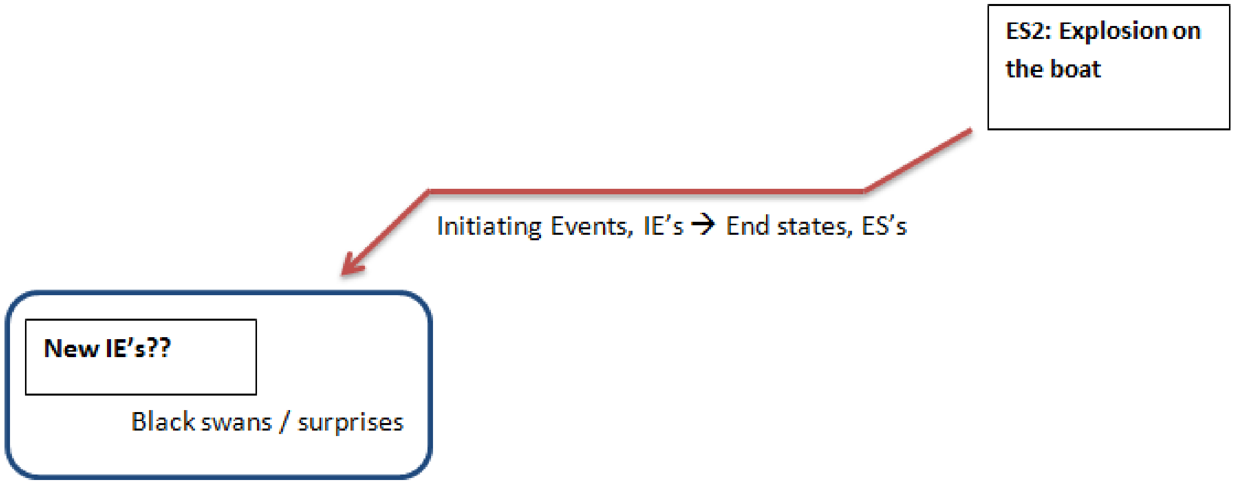

FIGURE 20: FINDING IE'S FOR ES2

Checklist for ES2 is listed in the table below:

ES3 - Explosion on the boat		
CHECKLIST	**SUBCATEGORY**	**DESCRIPTION**
Typical stages in life cycle of technical system	Manufacturing	Malfunction in the manufacturing process, tool not assembled properly
Typical dangerous stages in a system's functioning	Periods when tests and maintenance occur	Damaged tool when testing due to inexperienced personnel
Typical weak and dangerous zones	Zones subjected to high intensity fields	Dangerous zone on drill floor when running tool with punching mechanism/shooting guns down in the well
	Zones of potential energy	Chemicals stored near hazardous elements or other hazardous chemicals leading to an early detonation
Typical harmful impacts	Mechanical	When running in hole with tool one can drop tool and encounter mechanical damage
	Chemical	Chemicals used for detonation have been exposed to unfamiliar action and does not detonate when planned

	Electrical	Failure in wireline cable causing resulting in failed detonation
	Information	Poor information between crews during handover

TABLE 14: CHECKLISTS FOR ES2

The conclusion is that there is nothing special during subsea PnA that can cause an explosion on the boat that are of any difference from conventional PnA.

However, it is of importance to note that explosions as a result of a blowout will be handled differently on a boat compared to a rig or a platform. This is a bit off topic as it is more towards a preventive way of thinking, and not "how to create an explosion", but it is of importance to note. If a blowout would occur, a boat will be able to move faster away from location than a semi-submersible. The semi-submersibles are using risers where all fluids are pumped through the riser. If a kick occur and one is to move off location, one will need to displace the riser to seawater first, and then disconnect the riser. This operation is time consuming and not required if using a boat, as a riserless mud system is used. So a "move off location" operation would be executed much more efficiently.

The third end state, ES3, we want to create initiating events related to is "poor well isolations". We have the following figure that demonstrates the flow from the ES "poor well isolations" to new IE's for subsea PnA:

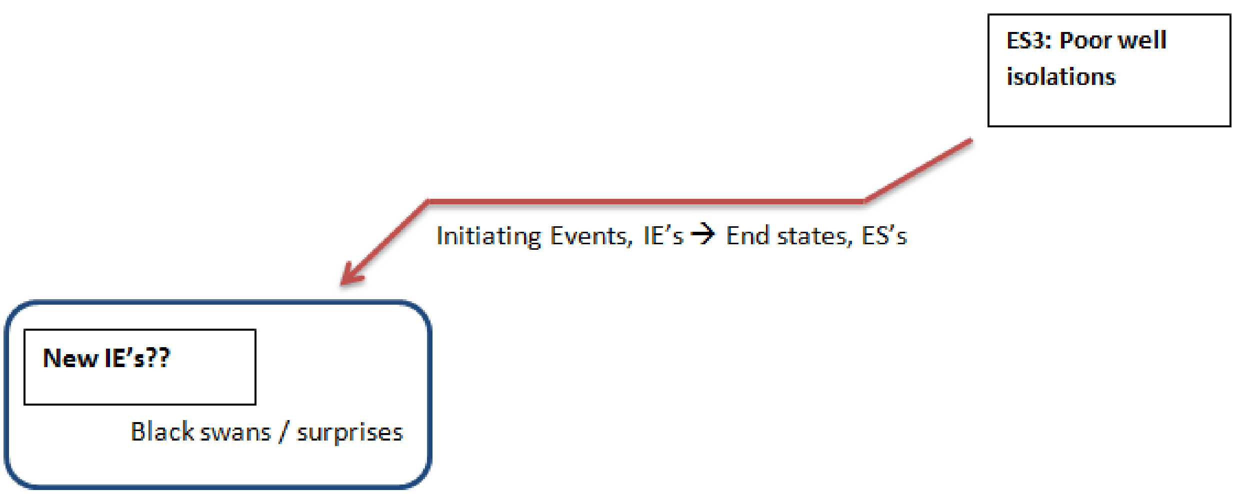

FIGURE 21: FINDING IE'S TO ES3

The below table list the different checklists that were found to be applicable for the ES3. As mentioned for the other tables containing checklists, description for both conventional PnA and subsea PnA is included.

CHECKLIST	SUBCATEGORY	DESCRIPTION
Typical weak and dangerous zones	Conflict zones	*Lack of data from older well*s - do not know whether it is a good cement job or not when casing was cemented in place
	Conflict zones	*Lack of data from older wells* - casing has corroded due to acid gas which was not expected when selecting the casing, but has developed over the last decades
Typical harmful impacts	Pressure	*Older wells* - collapsed casing due to change in reservoir pressure/depletion
	Mechanical	*Older wells* - corrosion on casing can cause migration of formation gas and fluids to surface
	Chemical	Insufficient cement job due to poor cement chemicals
	Information	General reduced information about older wells causing a higher risk to plug them
Typical weak and dangerous zones of system	Flow concentration zones	Too low flow rate when pumping cement resulting in poor cement job, leading to contamination of cement.

TABLE 15: THE TABLE LISTS CHECKLISTS FOR ES3

The conclusion is that there are no specific differences in subsea PnA compared to conventional PnA in regards to poor well isolations. A poor cement job can result in poor well isolations, however a poor cement job will be discussed below in ES5 and we will try to create IE's to that scenario later. However, there are many examples of poor well isolations, and one of them is the gas leak on the Total's Elgin field in 2012. The leak occurred during decommissioning and PnA of the well 22/30c-G4. No injuries were reported, but as the Total's safety manager said "if that source of gas finds an ignition source, there will be a fire" (Gosden 2012). There is no doubt that a gas leak can originate a fire and explosion, and in worst case; fatalities. When it comes to well isolations on older wells, wells that have been producing for many years, there is a higher chance of gas leaks as the casing integrity is less certain. With this in mind, we know from ES2, explosion on boat, that a boat can move off location in less time if required as no riser is present in case an explosion occurs due to a leak. Other than this, there are no distinct differences in subsea and conventional PnA when it comes to poor well isolations.

The Fourth ES is "stuck tools and pipe" in well, and we ask the question "how can we cause stuck tools and pipe in subsea PnA?" The following figure illustrates the situation:

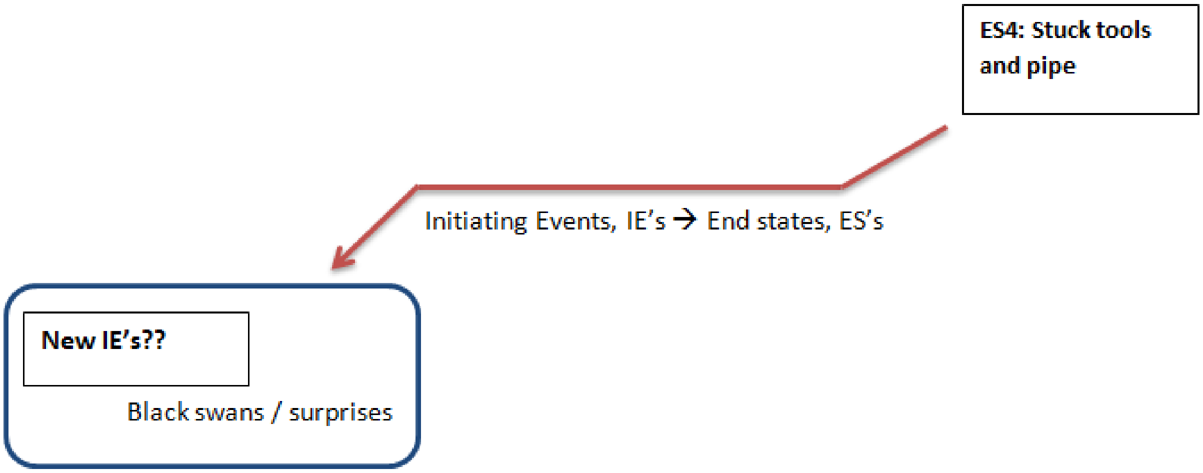

FIGURE 22: FINDING IE'S TO ES4

Reasons for stuck pipe or tools are listed in the table below where different checklists that are suitable are applied:

CHECKLIST	SUBCATEGORY	DESCRIPTION
Typical weak and dangerous zones	Zones subjected to the action of high intensity field	When cutting and retrieving casing on older wells, casing can be stuck due to settling of mud
	Conflict zones	Older wells – stuck tools and pipe due to collapsed and corroded casing
Typical disturbances of flow in the system		When cutting and retrieving tubing it is required to cut the control lines first, otherwise the cutting blade can get stuck
Typical harmful impacts	Mechanical	Different mechanical cutting tools (used for cutting tubing and control lines) are likely to get stuck if it is not cut in compression
Typical resources capable of producing harmful impacts	Quality of cement	If the zonal isolation of the first plug is poor, it is required to perform a cement squeeze job. When performing a cement squeeze job it is most likely pumped excess cement as it is hard to know how much is needed. The excess cement is needed to be circulated out, and this can cause stuck pipe if cement has cured.

TABLE 16 THE TABLE LIST CHECKLISTS FOR ES4

Based on above checklists there are no evident differences between subsea PnA and conventional PnA. Stuck pipe and tools can occur in both cases, and a vessel as opposed to a rig will not help the situation.

The next ES we are looking at is “poor cement job”. We could say that the cement job is the most crucial job in a PnA situation, as it is the cement plugs which barriers off reservoir fluids from surface. We have the following situation where initiating events are to be created from the end state “poor cement job”:

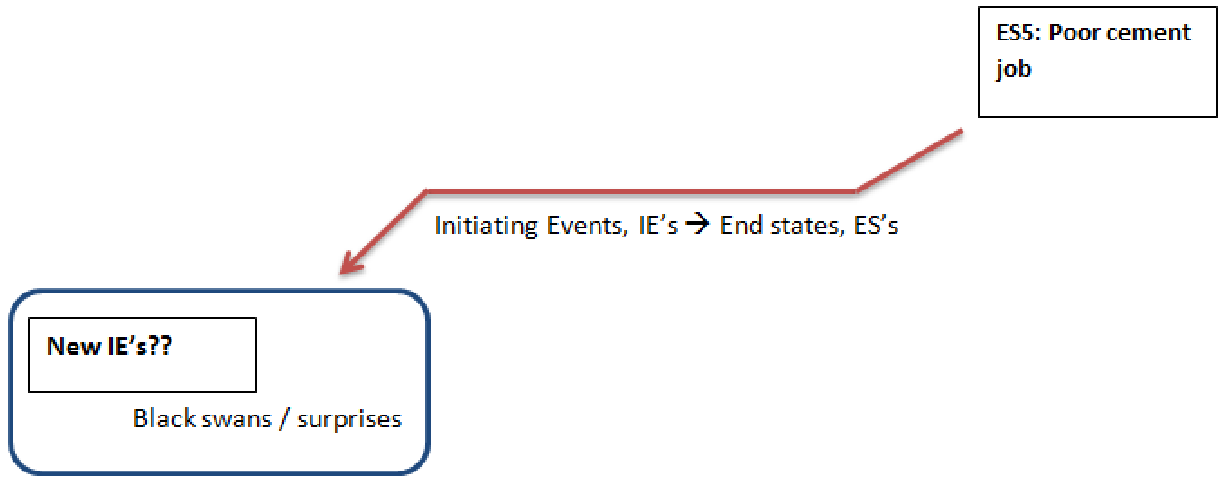

FIGURE 23: FINDING IE'S TO ES5

We are asking the question "how can we cause a poor cement job when performing subsea PnA?" and reasons for a poor cement job are listed in the table below:

CHECKLIST	SUBCATEGORY	DESCRIPTION
Typical stages in life cycle of technical system	Manufacturing	Cement in poor shape due to contamination of cement
	Transportation	When loading cement powder from shore to boat cement can get contaminated if the wrong hose is used due to inexperienced personnel
Typicak dangerous stages in a system's functioning	Periods of change in personnel	Poor cement / chemicals have arrived boat and this is not communicated to either shore or colleagues
Typical weak and dangerous zones	Flow concentration zone	If cement is pumped and displaced with insufficient pump rate, the cement job will end up bad and will not seal the formation properly.

	Conflict zones / weak	Depleted reservoirs are contributing to a narrower pressure window which can result in fracturing the formation when pumping the cement
Functional	Subsea equipment	• Malfunction in subsea pump • Parted mud return line due to poor maintained connections
Weather		Heavy currents causing a turbulent effect leading to spill to sea

TABLE 17: CHECKLISTS FOR ES5

Problems like poor pump rate, poor cement delivered to rig and wrong mixing ratio of cement chemicals are as prone to occur during conventional PnA as during a subsea PnA. What is special for subsea PnA in causing a poor cement job is the subsea equipment. As it has been stressed; instead of using a riser like conventional PnA, subsea PnA uses riserless mud recovery system. This system consists of a wellhead interface module (WHIM) which is installed onto the low pressured wellhead, mud return line and a subsea booster pump. The WHIM collects drilling mud, cuttings or other fluids returning from the well. The mud return line is a hose connected from the WHIM to a subsea booster pump and then up to surface, see figure 2 for a reminder. When we ask the question "how can we cause a poor cement job" the following IE's is created:

- IE5.1 – Leakage through mud return line
- IE5.2 – Failure in subsea pump – no returns to surface
- IE5.3 – Strong currents leading to tangled return hose into umbilical hoses
- IE5.4 – Parted mud return hose due to heavy currents
- IE5.5 – Parted mud return hose when pumping cement

The mud return line will be pressure tested prior to cement jobs, yet a leak may still occur. Another scenario that can occur is a failure in the subsea booster pump. This pump is of great importance as the fluid is more or less "dead" when it comes up to seabed, and the pump is required to pump the fluid up to surface. Strong currents can have a great impact on the subsea equipment, and especially the mud return line. If this hose is parted during a cement job the whole operation can fail.

The last end state we are looking at is "emergency shutdown system not functioning", and we are asking how we can create failures related to the emergency shutdown system on the boat. We have the following situation where initiating events are to be created

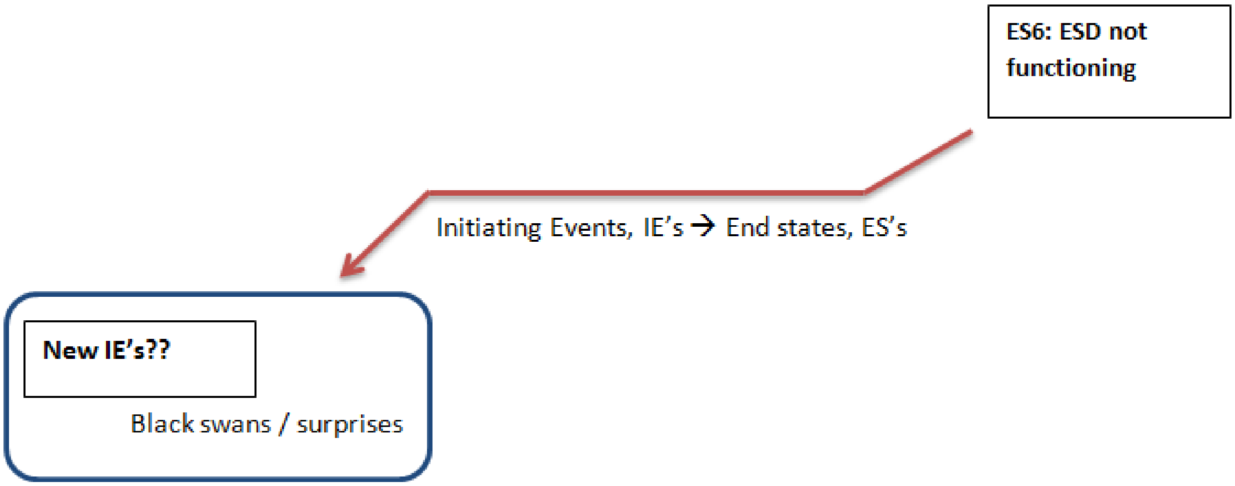

FIGURE 24: FINDING IE'S TO ES6

The riserless abandonment system will not have emergency disconnect capability as normally incorporated into a BOP because there is no riser. The control system will thus incorporate a modified ESD capability which, when activated, will disconnect the down lines, shear any conveyance in the SWID by operating the casing shear ram, close off the well using the blind shear ram, and lastly disconnect the umbilicals. The umbilicals are the critical link between the subsea equipment and the vessel; providing control, power and communication between the vessel and the subsea equipment. As all the subsea equipment use the umbilicals deployed from the vessel for direct hydraulic and electrical supply from surface, it is critical if the system is interfered. The system will, as a result, not be able to close the well in case an emergency. When we are asking the question "how can we cause a failure in the ESD system when performing subsea PnA?" the following answer is created:

- IE6.1 – Error in electrical or hydraulic power in umbilicals

The last four steps in the AFD still remain, and these steps are "invention of new solutions", "intensification of harmful effects", "analysis of harmful effects" and last "Prevention of harmful effects" – see chapter 3.5.2 for a full AFD analysis. However, these steps are intentionally left out as we now have managed to find events that lead to failures, which was the purpose of the thesis. Finding new solutions and analyzing the effects was not within the scope of this thesis. With that said, we are not done with the stepwise procedure invented in this thesis, and next will be step 3 – taking "old" relevant IE's and finding "new" ES's.

In this step we are seeking to find if there are any new ES's formed from the old IE's we already have. We are therefore interested to see if the conventional PnA events are giving us any new ES's in subsea PnA. We have the following figure to illustrate the operation we are now going to perform:

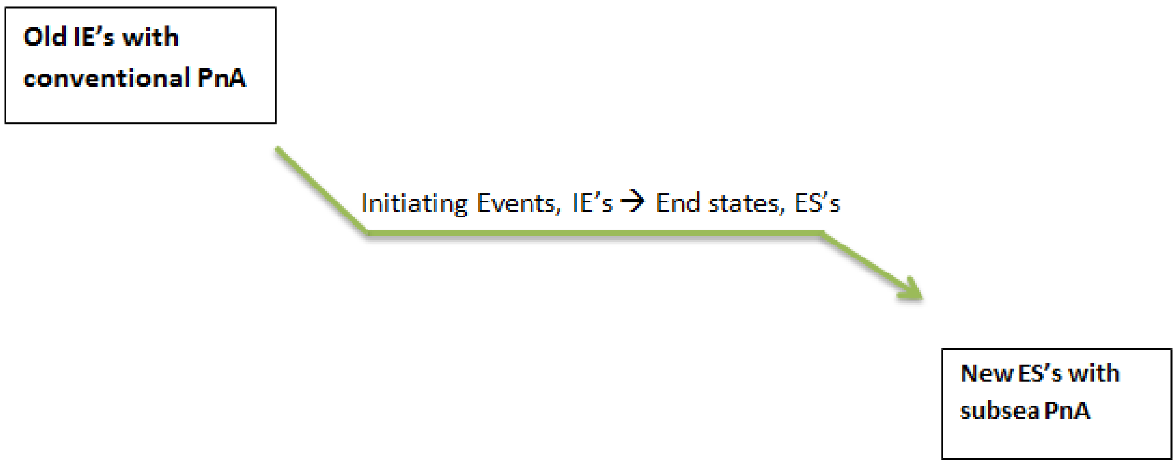

FIGURE 25: FROM OLD IE'S TO NEW ES'S

Table 4 in chapter 5.1 is showing old IE's leading to old ES's. We know from this table what caused the old end states, and we will use these old IE's to do the analysis.

The first scenario is chemicals handling, and the initiating events that leads to ES1, exposure to people and environment, are when mixing fluids and a rupture in riser or leakage when transferring fluids occurs. We ask the question "can these IE's lead to other ES's in subsea PnA than exposure to people and environment?" To our knowledge, these IE's will lead to the same ES's as in conventional PnA. The conclusion is that the potential new ES's remain the same as the old ES's.

The second scenario is explosives handling, and the initiating events leading to ES2, explosion on boat, is IE2a – blowout from kick and IE2b – explosives tools on boat. We ask if these IE's can lead to any new ES's in subsea PnA. We have discussed earlier in this thesis that a boat is able to react faster to an emergency response situation compared to a platform/semi-submersible, and the IE2a – blowout from kick, will as a result lead to less damage using a boat than rig as it can move faster from location. IE2b – explosive tools on boat is not judged to result in any new ES in subsea PnA. However, with IE2a – blowout from a kick, we can achieve a more benign end state in subsea PnA than in conventional PnA.

The third scenario is well isolations, and the end state is ES3 – poor well isolations. We ask the question "can the initiating events IE3a – poor cement job and IE3b – inadequate logging of casing, lead to any new ES's in subsea PnA?" IE3a is the same as ES5 – both of them are poor cement jobs. We will hence not go through a new analysis on new ES's on a poor cement job here. This analysis has already been done in chapter 5.2.

The fourth scenario is running in hole with pipe and tools. The end state, ES4, is stuck pipe and tools. The initiating event leading to stuck tools and pipe is hydrates forming in the well, plugging the formation. We ask the question "if a formation plugged by hydrates can result in any new ES's in subsea PnA other than stuck tools and pipe?" We anticipate that we don't get any new ES's when we are executing subsea PnA, as opposed to conventional PnA. Stuck tools and pipe would occur under seabed, and would not be related to the subsea equipment.

The fifth scenario is cementing operations and the end state is a poor cement job. We have all together five initiating events leading to a poor cement job:

- **IE5a:** Inadequate pump rate
- **IE5b**: Poor quality of cement
- **IE5c:** Not sufficient volume of cement
- **IE5d:** Cement not static for sufficient amount of time

We ask the question "Do any of the above initiating events result in new end states besides "poor cement job"?" For a, b, c and d there is no reason to anticipate that the events will lead to any new end states. If the above IE's occur, they will result in a poor cement job no matter subsea or conventional PnA.

The last scenario is the ESD system and the end state is that the ESD system does not work when needed. We have two initiating events leading to a failure in the ESD system:

- **IE1:** Automatic sensors (gas for example) not working or are covered with a sheet
- **IE2:** Lack of maintenance resulting in fault in electrical chain

Neither of these end states are anticipated to end up in new ES's. If the above IE's occur they will contribute to ESD failure, but not a new ES.

We have now tried to find new ES's to old IE's, and the next and last step in our stepwise procedure is to find new ES's from the new IE's we found in 4.2

In this chapter we will use the new initiating events we have invented in step 5.2, and see if they result in any new ES's. The operation we are performing now is illustrated in the figure below:

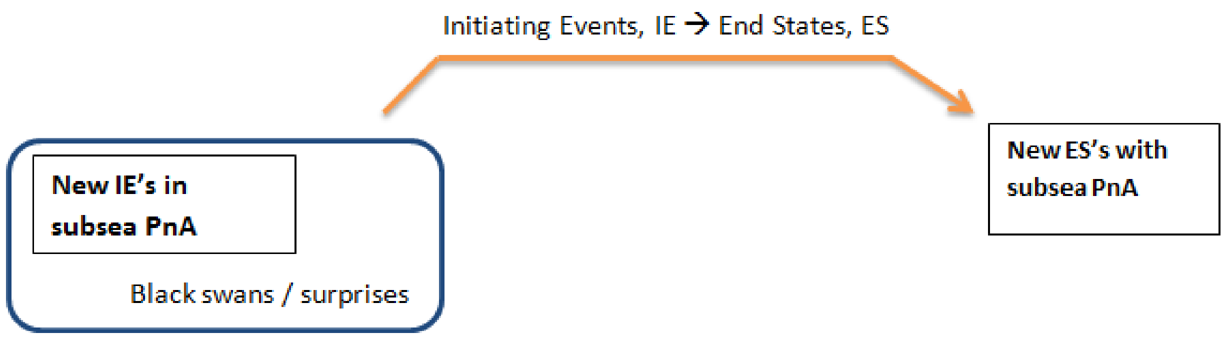

FIGURE 26: FINDING NEW ES'S FROM NEW IE'S

We have the following new initiating events:

- IE5.1 – Leakage through mud return line
- IE5.2 – Failure in subsea pump
- IE5.3 – Strong currents leading to tangled return hose into umbilical hoses
- IE5.4 – Parted mud return hose due to heavy currents
- IE5.5 – Parted mud return hose when pumping cement

- IE6.1 – Error in electrical or hydraulic power in umbilicals resulting in no communication from vessel and subsea

The first question we ask is for IE no. 5.1, and what end state will the initiating event "leakage through mud return line" result in. A leakage through the mud return line will result in volume control readings indicating losses of fluid in the well, which further can result in confusion between personnel thinking the cement is pumped into the formation. Hence, if the leak is not detected with the remotely operated vehicle (ROV), the operation might be stopped unnecessary. This can, as a worst scenario, end up in drill pipe full of hard cement and a well that is not cemented. We get the following new ES:

- ES5.1 – Drill pipe and tools filled with hard cement

The second new IE is IE5.2 – failure in subsea pump. If a failure in the subsea pump occurs, the fluid will not be pumped up to surface. We get the same scenario as with IE5.1 – confusion between personnel thinking cement is pumped into the formation. This is obviously worst case scenario as there will be indicators on the subsea pump indication failures; however we are thinking "the worst case that can go wrong". We are anticipating that:

- ES5.2 = ES5.1 =Drill pipe and tools filled with hard cement

The third end state that was invented for a poor cement job was "strong currents leading to tangled mud return line into umbilical hoses". This can cause a stop in operation, and specialty tools may have to be shipped out in order to rectify the problem. We will call ES5.3 for the following:

- ES5.3 – Stop in operation

The fourth IE we invented for a poor cement job was "parted mud return hose due to strong currents". If the currents are too strong for the mud return hose to handle, the hose will disconnect. With a high pump rate this can cause a major spill to sea. We get the fourth end state:

- ES5.4 – Major spill to sea

The fifth IE we are going to find an ES to is "parted mud return hose when pumping cement". If we assume that the mud return hose disconnects while pumping cement in a situation where excess cement has been pumped, this IE is critical. This may result in partly cemented seabed and party cemented well, and as a worst case – cement being pumped on the subsea equipment leading to major failures in the equipment. We get the last end state:

- ES5.5 – Cemented subsea equipment

The sixth and final IE we are going to find new ES's to is IE6.1 "Error in electrical or hydraulic power in umbilicals". This IE is very critical as it can result in no communication from the vessel and the equipment subsea. The worst thing that can happen if IE6.1 occurs is lost communication between equipment subsea and the vessel, which can further result in not being able to shut in the well if a kick is taken.

We have now created new ES's from the new IE's we created in chapter 5.2.

From step 1 to step 4 in our four step procedure we have verified and created old IE's and new IE's and ES's. To get a better overview of the IE's and ES's we have created, the below table is made. The table below displays which of the IE's and ES's that are applicable for conventional PnA and Subsea PnA. Old IE's are applicable for both conventional PnA and subsea PnA, which we verified in step 1. The new IE's created in step 2 are only applicable for subsea PnA. The new ES's created in step 4, on the other hand, are mainly applicable for subsea PnA. However, new ES1, 2, 3, 4 can occur during conventional PnA, but ***not*** under the circumstances we have created them, seeing that they are created from new IE's only applicable for subsea PnA.

		Conventional PnA	Subsea PnA
Old ES's	ES1: Exposure to people and environment	x	x
	ES2: Explosion on boat	x	x
	ES3: Poor well isolations	x	x
	ES4: Stuck tools and pipe	x	x
	ES5: Poor cement job	x	x
	ES6: ESD not working	x	x
OLD IE's	IE1a,b: Exposure when mixing and transferring	x	x
	IE2a,b: Explosion from blowout and tools	x	x
	IE3a, b: Stuck tools from poor cement job and inadequate logging of casing	x	x
	IE4: Stuck tools from hydrate formation	x	x
	IE5a-d: Poor cement job by inadequate pump rate, poor cement quality, not sufficient cement volume, cement not static for a longer time	x	x
	IE6a,b: Automatic sensors not working, lack of maintenance	x	x
New IE's	IE5.1: Leakage through mud return line		x
	IE5.2: Failure in subsea pump		x

	IE5.3: Strong currencies leading to tangled return hose into umbilical hose		x
	IE5.4: Parted mud return hose due to heavy currencies		x
	IE5.5: Parted mud return hose when pumping cement		x
	IE6.1: Error in electrical or hydraulic power in umbilicals		x
New ES's	ES5.1: Drill pipe and tools filled with hard cement	(x)*	x
	ES5.2 = ES5.1	(x)*	x
	ES5.3 : Stop in operation	(x)*	x
	ES5.4: Spill to sea	(x)*	x
	ES5.5: Cemented subsea equipment		x

TABLE 18: OVERVIEW OF THE IE'S AND ES'S IN SUBSEA PNA

*The * notation means that it can happen during conventional PnA, but not under the circumstances in which we have created them.*

We can conclude from this table that all of the old IE's and ES's can occur in conventional PnA and subsea PnA. We can further conclude that there are more new IE's leading to failures in subsea PnA than in conventional PnA. The new ES's created from the new IE's are only applicable if they are derived from new IE's. However, the new ES's can, under other circumstances, not analyzed in this thesis, occur for conventional PnA, but they cannot occur due to the new IE's.

6. DISCUSSION

This chapter will discuss the model we have developed, strengths and weaknesses and future applications.

6.1 THE MODEL AND AFD

Conversations with different people in the industry have revealed that some HAZID's (or other risk assessments) are not involving or engaging all participants as experience lead them to think that "they know it all". The question of risk is, to some extent, not challenged enough. The "copy paste" operation from other HAZID's is an easy way out when one is not "bothered" to think of other hazardous threats that can occur. The question "how can we engage all participants and make HAZID's a creative process?" arose after having conversations with people in the industry. In this thesis, a model for identifying unwanted events and end states has been created. This model is first and foremost illustrating that initiating events lead to future end states. It further illustrates that we have, for a given scenario, old and new initiating events leading to old and new end states. What stands out on this model compared to other risk assessment models is that the way of thinking is reverse – we are going from end states to initiating events. The procedure is a four step procedure, and we are going both ways – from initiating events to end states and vice versa. However, it is the backwards way that stands out. As stressed, the model is based on Anticipatory Failure Determination. AFD is a very extensive procedure that is too comprehensive, takes too much time, effort and resources to carry out. One could argue that this is one weakness the model that has been developed holds. The whole AFD procedure, going from step 1 "Formulate the original problem" to step 10 "Prevention/Elimination of harmful effects", is so extensive that one would struggle to get the industry to go through with a process like that. This thesis did not go through all the steps in the AFD analysis, and stopped at step 6 – Utilization of the AFD knowledge base. We have found resources and different checklists for each ES in this thesis. The resources and checklists in step 5 and 6, respectively, are only up for confusion for a reader who is not familiar with the AFD process or the activity that is studied. When performing step 2 in the four step procedure, the resources and the checklists in the AFD procedure did not bring any valuable contribution to the results in this thesis, perhaps only confusion. Especially for a reader who is not familiar with the AFD process. On the contrary, it is not fair to say that the AFD contribution is a weakness for this model as the model was inspired by this work. What is important to highlight is that the core idea with AFD is to ask the question "How can we make this system fail?" and it is this question that is of value for the model. The whole AFD procedure with the 10 different steps is not of the same value for the model. It is believed the new IE's and ES's we created in this thesis were not dependent on the tables of resources and checklists, and we could have created events and end states without them. However, the idea behind the resources and checklists is good, but does not work efficiently when only one person is performing the analysis. With a group of people who are able to see things differently, the resources and checklists can contribute to taking the creativity a step further.

As discussed, the case with subsea PnA ended halfway through the AFD procedure, and if one is only interested in finding unwanted events, and not preventive measures, it is not required to go through the whole process of AFD. In step 2 in the four step procedure we identified new IE's from old ES's by going through step one to six in the AFD process. In hindsight, this was not required in order to create new IE's. We found the IE's by only asking the question "how can we make this system fail?", and not by generating the tables of resources and checklists. This is the reason the AFD procedure was not applied in step 3 and 4 – finding new ES's from old IE's and finding new ES's from new IE's, respectively.

As mentioned above, the model illustrates that initiating events lead to future end states. In chapter 3.3 we introduced scenario analysis which includes different principles. We can say that the model we have developed is similar to figure 4; the principle of initiation, seen in section 3.3.2. In our model, the path of success is interrupted due to the occurrence of an ES, so the event does not reach the point of success. As seen in figure 7 in section 3.3.6, middle states, MS, originates between the initiating event and the end states. The model we have developed does not give room for any MS. However, it would be possible to implement MS in the four step procedure when creating initiating events or end states. As an example we can take the IE5.5 → ES5.5. We have IE.5.5: Parted mud return hose when pumping cement, and ES5.5: Cemented subsea equipment. If we would implement MS for this scenario, we would say that IE5.5 → spill to sea → ES5.5. Spill to sea would in this case be our MS. We know that "spill to sea" is ES5.4, and MS's tend to be alike either IE's or ES's. We have thus decided not to give MS's attention in the developed model.

The model itself, without the AFD procedure, stimulates to creative thinking, and people need to think differently in order to identify the risks. The model will contribute to creative thinking where people need to think outside their comforts zone and outside the box. The way of asking the question "how can we create this failure?" provides captivation, engagement and a sense of responsibility and commitment where one is able to have a stimulating time performing the hazard identification. What is important to note with the model and the mindset of "creating failures" is to have high skilled people on the team. Creating failures alone is a demanding process and does not necessarily end up in plausible initiating events or end states. If people of high technical understanding from different areas join the inventive group, it is believed that the initiating events and end states that are created will be of value and significance.

6.2 THE MODEL AND THE BLACK SWAN CONCEPT

We have mentioned the black swan concept in chapter 3.4 and we are known with the categories of a black swan. This model will not be able to identify unknown unknowns as we do believe that it is hard to create something that is beyond ones imagination. As for unknown knowns, articulated by Aven (2014) as *"events that are not captured by the relevant risk assessment, either because we do not know them, or we have not made a sufficiently thorough consideration."* it is more likely to identify these than unknown unknowns, even though this category is hard to identify as well. However, it is most likely "knowns" that are within the reach for this model to identify. Knowns are events that are known, but their probability is seen as negligible. Human beings have a tendency to deny events that are not seen as significant. An example for the subsea PnA can be that an underwater volcano or an earthquake will result in a tsunami that causes the vessel to tip over. Another example can be that a shark bites off the mud return line. Both of these events are humans capable of creating. Many would argue that this "will never happen" and deny the events. If the denial phenomenon is left out when creating failures with this model, it is possible to identify the known category of a black swan.

6.3 THE MODEL AND FUTURE DEVELOPMENT & APPLICATION

This model can apply for areas other than subsea PnA. It can also apply for other new areas of technology or operations where risks are in need of identification. It is not a good model to use if there is limited knowledge of the phenomena itself as we do need old end states when finding new initiating events. It is not a good model to use when developing a new type of medicine to a virus we have no knowledge of, for instance. So a condition to be able to use the model is to have fundamental knowledge of the scenario that is going to be analyzed. We have exemplified that the model works for everyday scenarios like taking a bus versus driving a car. We have further illustrated the usage of the model with subsea PnA, where new IE's and ES's were created. The health industry is another area the model can apply to. An example can be when people are recovering from accidents. We know the worst condition the patient have, and can from that condition ask the question "how can we cause this condition in the recovery process?" If the patient knows all the initiating events leading to a relapse of the injury, the patient will avoid all those events. Another area of usage could be quality management within the food industry. New food products are continuously entering the marked, and some food products are taken off the marked instantly due to poor demand. Maybe these products could have been designed better with the use of this model. The end state would have been "poor selling of product" and initiating events could have been created thereafter.

Visually, there is a resemblance between a bowtie diagram and the model we have developed. In a bowtie diagram, there is also room for preventive measures and control measures. The model we have developed is not designed to identify and show any preventive measures, at least not as a part of this thesis. The largest difference with our model is the backwards thinking – going from a hazard end state and finding the events that will cause that hazard end state. A bowtie diagram is only going from left to right, however with this model we execute analysis both ways.

For Halliburton's interest, an implementation of the model will add value and quality for future HAZID's, or other risk related assessments, as the model stimulates to creative thinking "outside the box". There is room for improvement of the model; such as implementing control and recovery barriers as in a bowtie diagram. So the model that this thesis presents is a good foundation for further development. It would take time and effort to implement a model like this to Halliburton's systems and procedures. With that said, if the result is more engaged participants contributing to new IE's and ES's, the time and effort is entirely worth it.

7. CONCLUSION

The objective for this thesis was to develop a model that identifies unwanted events. In addition, the objective was to use this model to identify unwanted events in subsea Plug and Abandonment.

A four step procedure has been developed which involves both forwards and backwards analysis. The developed model was inspired by the distinction of initiating events and end states. It was further inspired by Anticipatory Failure Determination, which is based on reverse analysis, where the main question asked is “how can we make this operation fail?”

The model does not only identify end states from initiating events, which one would think is the normal way to go, but also identifies initiating events out from known end states. Further, the model discovered six new end states in subsea PnA that can cause harm to operation and environment.

This model can also be applied to other areas where basic knowledge of the scenario analyzed is familiar. However, in order to implement this model to future HAZID’s or other risk assessments tools in Halliburton, there is a need for further development of the model.

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9. APPENDIX

APPENDIX A

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HAZARD IDENTIFICATION REPORT
CAMELOT WELL ABANDONMENT</td></tr>
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PROJECT MANAGEMENT</td></tr>
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<tr><td>Rev</td><td>Reason for Issue</td><td>Issue Date</td><td>Prepared</td><td>Checked</td><td>Approved</td></tr>
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INTRODUCTION

Energy Resource Technology (ERT) are the licensees for the Camelot Field, located in the Southern North Sea and the owners and duty holders of the Camelot CA fixed installation. The Camelot Field has ceased production and work is ongoing to permanently abandon the wells within the field and to dismantle and removed the Camelot CA installation.

The six well abandonment programme has been planned to be undertaken in three phases; Phase I has already been completed on all six wells.

The phases have been broken down into the following:

Phase I: Wireline operations - set and test the deep-set mechanical plug. Punch the tubing above the polished bore receptacle.

Phase II: Circulate well to kill fluid (seawater), place balanced cement plug on top of mechanical downhole barrier (combination of production packer and deep-set plug) and pressure test plugs. Perforate tubing above TOC in tubing and place 1000ft balanced plug on top of existing plug. Tag TOC down tubing.

Phase III: Cut tubing above the TOC, place a 1000ft balanced cement plug from cut depth. Recover tubing to position tubing above TOC and hang off in WH.

Cut tubing at 700ft, recover tubing to surface, punch 9-5/8" casing at a depth to allow a 500ft cement column be circulated into the 9-5/8" x 13-3/8" annulus through a cement retainer set above the casing punch. Spot a 200ft environmental cement plug on top of retainer inside the 9-5/8" casing. Cut 30", 20", 13 3/8" and 9 5/8" casing from below the mudline in a single operation.

All operations in the above programme will be carried out using the Seafox 7 jack-up/support barge.

As part of the preparations for undertaking the above workscope, a Well Abandonment Hazard Identification (HAZID) study was carried out on 20th February 2012. The results of this study are reported in the following sections.

ert risk assessment process

The following is an outline of the overall process for risk assessment adopted by ERT for well abandonment activities in the Camelot Field.

ERT RISK ASSESSMENT PROCESS	Energy Resource Technology Ltd undertake a three tiered risk assessment process, this ensures that adequate risk assessment is conducted during the planning and operational stages of the project and allowing input from a broad spectrum of personnel at all levels in the organisation. Level 1 - Risk Assessment: Is an onshore activity, it is a review completed by the personnel who have generated the procedures and those with managerial responsibility for the activities. This risk assessment will be completed to identify any significant hazards associated with the tasks and determine if indeed the procedures and resources are adequate to reduce the risks to ALARP. The content of the reviewed/revised operational procedures including output from the Level 1 - Hazard Identification and Risk Assessment will be issued to the offshore worksite including a briefing by the relevant Engineering personnel who developed the procedures. Level 2 - Risk Assessment: Is an offshore activity, it is a review completed at a managerial and supervisory level of the well operations, diving & interacting activities prior to commencement of work, by those knowledgeable and experienced in the operations with the most relevant and up-to-date information available. Typically attending the meeting will be Operations Manager, OIM, Wells Manager, Safety Engineer and Client Representative (if applicable, supplemented by technical expertise, as required. Completion of this second level ensures that adequate consideration is given to the most relevant and up-to-date actual; ‘Site specific hazards’ and environmental conditions, ‘Every perceived hazard’ is evaluated and risk assessed by those responsible for performing the activities and the inclusion of the ‘Current Status’ of interacting operations (i.e. Well Operations). This confirms that the ALARP demonstration completed in level one is still applicable. The output from the Level 2 Risk Assessment will be recorded in this Risk Assessment document. Level 3 Toolbox Talks: TBT's/TRAC’s will be completed
LEVEL 1 RISK ASSESSMENT SCOPE OF WORK	The Level 1 Well Abandonment HAZID was held to cover all safety related topics and works associated with the forthcoming project operations: 1.0 Pre-operations activities 2.0 Interfaces 3.0 Jack up positioning, supply boat operations, rig up 4.0 Well handover 5.0 Well abandonment 6.0 Demobilisation
LEVEL 2 RISK ASSESSMENT SCOPE OF WORK	The Level 2 Risk Assessment - HAZID Review Meeting will be held **onboard** to review the Level 1 Risk Assessment and any additional safety related topics and works associated with the forthcoming project operations:

SITE CONDITIONS	Field : Camelot Water Depth : 11m Tree Type : 6 x Surface Trees Planned Start Date : February 2012 Jackup : Seafox 7 (SF7)
MAIN HAZARDS	Ship Collision Heavy Lifts Loss of containment Pressure releases Breaking Containment Use of Explosives Use of chemicals NORM Handling
REF DOCS	Halliburton Barrier Policy Halliburton Operating Procedures Manual Camelot CA Safety Case ERT Onshore & Offshore Management System ERT Camelot CA SMS Interface Document (11533-CAM-PM-ID-005) ERT Camelot CA Emergency Bridging Document (11533-CAM-PM-BC-004) Camelot Phase III Programme Rev 2.2
CRITERIA APPLIED AT THE TIME OF THE REVIEW	Compliance with the above procedures is taken as read within HAZID.
HAZID CLOSEOUT	The actions arising from the HAZID will be tracked to closure by Risquest Ltd, who provided independent chair and scribe facilities during the HAZID session. Once all actions have been satisfactorily addressed, a formal HAZID Close Out Report will be produced. Projects may be audited as part of the ERT Audit Programme. In addition, as the work progresses, there may be changes which could impact upon the findings of the HAZID. Therefore, the General Manager shall continually monitor the changes agreed and assess the need to update the Risk Assessment as required. It should be noted that any items found to be Medium Risk where the HAZID Team could not offer any additional control measures to reduce this to ALARP are, as a minimum, highlighted as "SAFETY CRITICAL" items in all relevant procedures in line with ERT HS&E requirements and Management of Change procedures.
RECORD KEEPING	Electronic copies of the Closed-Out HAZID Reports will be forwarded to the ERT General Manager for inclusion in project files.

HAZID METHODOLOGY

The main objectives of the Level 1 Well Abandonment HAZID were as follows:

- To carry out a high level review to identify the hazards likely to be present during Phase II / III well abandonment programme that could lead or contribute significantly to a major accident event, or which present an occupational hazard to the workforce.
- To consider the likely cause and consequence of the hazard being realised and to evaluate both the initial and residual levels of risk presented by the hazard, before and after the application of control measures.
- To identify if there are currently suitable and sufficient control measures in place or if additional work is required to further mitigate the risks incurred in an operation of this type.

HAZID ATTENDEES

The following personnel attended the Level 1 Well Abandonment HAZID:

Glenn Andrews	Risquest Ltd	HAZID Chairman	glenn.andrews@risquest.com
Joan Sinclair	Risquest Ltd	HAZID Scribe	joan.sinclair@risquest.com
Mike Walker	Halliburton	QHSE	michael.walker4@halliburton.com
Neringa Dugnaite	Halliburton	HPM Co-ordinator	neringa.dugnaite@halliburton.com
David Cochran	Halliburton	HPM Support Eng	david.cochran@halliburton.com
Barry Robertson	Halliburton	WSS	barry.robertson@halliburton.com
Neil Kinnaird	Halliburton	Offshore Service Co-ordinator	neil.kinnaird@halliburton.com
Richard Mathieson	Halliburton	Cementing	richard.mathieson@halliburton.com
Martin Mutch	Halliburton	Service Co-ordinator	martin.mutch@halliburton.com
Iain Adams	Norwell	Project Manager	iain.adams@norwellengineering.com
Alastair MacKinnon	Norwell	Drilling Engineer	alastair.mackinnon@norwellengineering.com
Graeme Orr	Boots & Coots	Senior Tech Prof	graeme.orr@boots-coots.com
Doug Young	Helix	Offshore Project Manager	dyoung@helixesg.com
Bob Murdoch	Helix	Offshore Project Manager	bmurdoch@helixesg.com
Chris Jones	Helix	EHS Advisor	cxjones@helixesg.com
Jim Mackin	Helix	Special Projects Director	jmackins@helixesg.com
Richard Trayner	Helix	Project Manager	rtrayner@helixesg.com
Derek Ball	Epic	Camelot OIM	derek.ball@epic-ltd.com
Glen Falco	Epic	Project Manager	glen.falco@epic-ltd.com

Tony Williamson	Epic	Camelot OIM / Onshore Support	tony.williamson@epic-ltd.com
Eamonn McGennis	ERT	General Manager	emcgennis@helixesg.com
P De Weers	Workfox	Technical Safety Eng	pdw@workfox.com
A Eygenroom	Workfox	Rig Manager	aem@workfox.com
Mike Driscoll	Workfox	Seafox 7 OIM	oimsf7@workfox.com
Greig Blair	FMC	Service Technician	greig.blair@fmcti.com
Barry Elliot	Odfjell	Casing Technician	lambrettalad@gmail.com
Billy Cooper	Odfjell	Ops Supervisor	WICO@odfjelldrilling.com
David Watson	Tyco	Electrical Interface	davewatson@tycoint.com
Stephen Malcolm	Tyco	Mechanical Interface	smalcolm@tycoint.com

Hazid date & location

The HAZID was held on Monday, 20th February 2012 in the Menzies Hotel, Dyce, Aberdeen.

Conclusions

HAZID Findings

The Camelot Well Abandonment HAZID produced a total of 22 actions. Whilst it is recognised that these all require resolution prior to the commencement of the operation, none are considered to have a significant impact and therefore workscope planning can progress as required.

Copies of the HAZID worksheets are given in Appendix I and copies of the Action Sheets in Appendix II.

6.2 Risk Assessment

Each hazard identified as having a significant consequence on personnel, assets or the environment was assessed according to the undernoted hazard matrix (Figure 1). In every case, classification was based on the worst potential outcome, which in most cases, was the potential for personnel injury / harm. Risk was assessed on an initial basis, and again to determine residual risk following the application of identified control measures.

The all cases, residual risk is calculated as 'low' and therefore acceptable according to ERT's tolerability criteria, assuming that all identified risk control measures are put in place prior to each operation taking place.

FIGURE 1 - ERT RISK ASSESSMENT MATRIX

		PROBABILITY				
		A	B	C	D	E
SEVERITY	1	L	M	H	H	H
	2	L	M	M	H	H
	3	L	*L*	M	M	H
	4	L	L	L	M	M

SEVERITY

CATEGORY	DEGREE	DESCRIPTION
1	CATASTROPHIC	• Total plant/equipment loss • Potential for fatal injury • Work suspended indefinitely • Full scale major pollution incident response
2	MAJOR	• Major damage to plant/equipment • Serious injury to personnel • Work interrupted > 12 hours < 48 hours • Environmental incident reportable to Reg Authorities
3	CRITICAL	• Damage to plant/equipment • Injury to personnel • Work interrupted for > 1 hour < 12 hours • Breach of leg, but control within the capability of worksite
4	MINOR	• Minor damage to plant/equipment • Minor injury to personnel • Work interrupted < 1 hour

PROBABILITY

LEVEL	DESCRIPTION	INDIVIDUAL FAILURE MODE
A	IMPROBABLE	• So unlikely that occurrence may not be experienced.
B	REMOTE	• Unlikely but possible to occur during project
C	OCCASIONAL	• Likely to occur sometime during project
D	PROBABLY	• Will occur several times during project
E	FREQUENT	• Likely to occur frequently

WOUK'S RISK TOLERABILITY CRITERIA

HIGH – Totally unacceptable. Requires further assessment.

MEDIUM – If control measures cannot reduce this, it shall as a minimum, be highlighted as a "Safety Critical" item in all relevant procedures.

LOW – Adequate control measures are in place.

APPENDIX I - HAZID WORKSHEETS

1.0	**Pre-operations activities**											
1.1	Legislative Compliance.	Failure to complete / obtain required permits / consents / regulatory acceptance documentation prior to commencement of operations.	Schedule delay, potential prosecution and impact on company reputation.	1	B	M	CON documentation has been submitted to the HSE on 12 January 2012. HSE have returned with requests for further information (SMS and ER documentation). This is being finalised and will be submitted 21/02. PON 15F details (updated following IWOPs meeting) have been submitted to DECC electronically (by ERT in consultation with Halliburton). Copies of the PON documentation will be issued to PON Holder following DECC approval. Status of other required permissions, etc are given on the project Approvals, Permits & Consents Register.	1. C Jones to complete remaining documentation and submit to HSE. Action Party: C Jones Date: 22/02/12 2. Define which post is to be responsible for holding the PON and collating associated information. Action Party: E McGennis Date: 24/02/12	1	A	L	
1.2	PTW.	Potential for conflict with more than one permit system in operation.	Miscommunication, errors in the execution of workscopes.	3	B	L	Interface documentation defines application of permit systems on each installation. Work on SF7 undertaken under Workfox system, work on Camelot uses ERT system.	Confirm interface permit requirements for companies which will be working across both installations. Action Party: C Jones Date: 24/02/12	3	A	L	
2.0	**Interface Arrangements**											
2.1	F & G systems.	System malfunction.	System fails to operate in an emergency.	2	B	M	Function testing prior to commencement of operations. IVB independently witness function test.	Carry out function test of F&G system once bridge systems are connected. Action Party: Camelot OIM	2	A	L	

								Date: 01/03/12				
2.2	ESD.	System malfunction.	System fails to operate in an emergency.	2	B	M	Function testing prior to commencement of operations.	Carry out function test of ESD system once bridge systems are connected. Action Party: Camelot OIM Date: 01/03/12	2	A	L	
2.3	ESD on Camelot.	Live equipment on SF7 during potentially hazardous condition on Camelot.	Equipment on SF7 continues to operate, however this is beneficial during certain operations, e.g. cementing.	4	A	L	Radio communications will be used to determine optimal course of action on SF7 in the event of Camelot trip.		4	A	L	
2.4	ESD on SF7.	Operations may continue on Camelot during potentially hazardous condition on SF7.	Operations on Camelot continue.	4	A	L	Radio communications will be used to determine optimal course of action on Camelot in the event of SF7 trip.		4	A	L	
2.5	Comms systems.	System malfunction.	Inability to communicate.	4	C	L	SF7 PA and telephone systems are to be extended to Camelot. Radios are available as back up, giving redundancy of system provision. Function testing prior to commencement of operations.	Carry out function test of comms system once bridge systems are connected. Action Party: Camelot OIM Date: 01/03/12	4	A	L	
2.6	Navaids.	Two Navaids systems in operations.	Potentially unsynchronized Navaids, confusion for shipping in the vicinity.	1	B	M	Proposed to turn off Camelot navaids lights for the duration of the operation. Notification has been given to interested parties.		1	A	L	
	Deluge.	None is required following well decommissioning.		-	-	-						
3.0	**Jack up positioning, supply boat ops, rig up**											

3.1	Move barge on to location / deploy gangway.	Collision between barge and Camelot CA platform.	Damage to either or both installations.	2	B	M	Rig move procedures for move onto location (this phase of the operation has been completed). Gangway positioning subject to IVB verification.		2	A	L	
3.2	Camelot CA heli-deck removal from service.	Camelot CA heli-deck remains in service.	Potential for helicopters to continue to use heli-deck if not correctly marked.	1	A	L	Equipment for marking heli-deck as out of service provided by Camelot. CAP 437 specifies heli-deck de-commissioning requirements.		1	A	L	
3.3	Deck protection / grating removal.	Mechanical / manual handling and dropped objects.	Potential personnel injury, damage to installations.	2	B	M	Refer to ERT /RA/TW-004 - Remove Grating above Well Slots for Well Operations Risk Assessment. Well slot cover plate is provided for wirelining operations.		3	B	L	
3.4	Handrail removal in vicinity of gangway.	Man overboard.	Personnel injury.	2	B	M	Close standby from ERRV. Harnesses / fall arresters, look-outs during removal phase. Scaffold barriers post removal.		3	B	L	
3.5	General hazards - safe access / egress.	Movement of personnel before gangway is in place.	None identified, this is normal operation on Camelot.	-	-	-			-	-	-	
3.6	General hazards - safe access / egress.	Movement of personnel between SF7 and Camelot CA platform once gangway bridge is in place.	Personnel unable to return to SF7 if gangway connection unavailable.	4	B	L	Gangway connection / disconnection procedures. Bridge is barriered off if adverse weather constraints are reached. Tannoy system to notify personnel of need to return to SF7. Control of personnel movement across gangway via T Card system, provided by SF7. Number of personnel on Camelot is 2 minimum, 22 maximum.		4	A	L	

3.7	Supply boat approach.	Collision with Camelot platform. Collision with Seafox 7.	Potential personnel injury, damage to installations	3	C	M	Marine procedures, permission given by SF7 OIM to approach either installation. Camelot OIM will require to give permission in the event that Camelot crane is in use during supply boat approach. SIMOPs matrix applies.		3	B	L	
3.8	Supply Boat Offloading - Crane operations.	Overhead loads. Dropped objects. Swinging loads. Shifting loads. Restricted space/access. Manual handling of equipment/stores. Equipment positioned incorrectly on deck. Equipment not secured sufficiently. Handling of flammable & hazardous substances.	Injury to deck crew / Halliburton crew / supply boat crew. Damage to platform / barge / supply boat.	2	C	M	Deck plans / loading plan for supply boat to specify order that equipment is offloaded. LOLER inspection / certification of lifting equipment. Pre-slinging of Halliburton loads. Hazardous goods notices are provided. Loads pre-assessed as simple / complex lifts, complex lifts will require a lifting plan. Manifest to describe cargo contents and identify potentially flammable / hazardous substances. SF7 is capable of filling tote tanks for transmission to Camelot, should this be required.	Single point shipment contact (s) to be established and shipping arrangements to be finalised at Aberdeen and Gt Yarmouth. Action Party: R Trayner Date: 23/02/12 HALLIBURTON to issue deck plan for kit. Action Party: Neringa Dubnaite Date: 23/02/12	2	A	L	
3.9	Supply Boat Offloading - Crane operations.	Dropped loads.	Injury to deck crew / Halliburton crew / supply boat crew. Damage to platform / supply boat.	2	C	M	DROPS survey carried out on SF7. DROPS training provided by ERT / Helix (this can be done either offshore or onshore). Communication drills prior to ops starting. **TBRA –** Working at height. **TBRA -** Housekeeping.	Arrange to provide DROPs training for all personnel who require this. Action Party: E McGennis Date: 24/02/12	2	A	L	
3.10	Supply Boat Offloading - Crane operations.	Loss of power during lifting ops.	Loads left suspended.	2	B	M	Manual lowering of crane is available for SF7 crane, to be checked for Camelot crane.	Check whether manual lowering of Camelot crane is available. Action Party: Glen Falco	2	A	L	

								Date: 24/02/12				
3.11	Supply Boat Offloading - Crane operations.	Loss of comms between crane driver / banksmen. Loss of comms between banksmen and supply boat deck crew.	Loss of control of lift path. Dropped objects.	2	B	M	Banksman is remote from lifting operation. For marine operations, VHF radios will be used. Hand signals are available but operations are generally halted in the event of loss of primary comms system. All personnel involved in operations to attend TBT prior to job commencing. Comms procedures, including dedicated comms channels. Actions to be taken in the event of comms breakdown or emergency alarms have been identified. Daily comms system checks are undertaken as part of overall crane checks.		2	A	L	
3.12	Supply Boat Offloading - Crane operations.	No / poor line of sight between crane driver and banksmen.	Error in execution of lifts. Potential injury to banksmen from moving loads.	2	B	M	Radio control. 2 banksmen can be used.		2	A	L	
3.13	Supply Boat Offloading - Crane operations.	Adverse weather.	Increased dropped / impact potential from swinging loads.	2	B	M	Adherence to adverse weather policies, according to which crane is being used. In case of differing criteria, then the most stringent policy applies. Lifting requires ultimate agreement of crane operator / vessel masters.	Capture primacy of adverse weather policies within interface document. Action Party: C Jones Date: 22/02/12	2	A	L	
3.14	Supply Boat Offloading - Lifting and skidding operations.	Parting of slings/wires, damage to decks. Dropped objects.	Personnel injury, equipment damage.	2	B	M	**TBRA -** Lifting Of Equipment using the Deck Crane. **TBRA -** Deck Movement Operations. Normal DO precautions, e.g. equipment certification, LOLER requirements, IVB verification. No skidding of heavy equipment is	Review and confirm optimal IBC handling arrangements. Action Party: M Mutch Date: 24/02/12 Source pallet lifter. Action Party: G Falco	2	A	L	

							required for these operations.	Date: 24/02/12				
3.15	Rig up Deck Equipment on SF7 and Camelot CA.	Dropped Objects. Manual Handling. Operation in restricted / congested spaces. Inter-deck transfer of loads.	Personnel injury, equipment damage.	2	B	M	Deck plans. Lifting plans. LOLER inspection / certification of lifting equipment. Use of trained and competent personnel. Use of cargo nets / boxes for inter deck transfer of equipment	Investigate provision of cargo baskets complete with door and whether any other specialist lifting equipment is required. Action Party: G Falco Date: 24/02/12	2	A	L	
3.16	Storage of hazardous materials.	Hazardous / flammable materials.	Potential impact on escape from crane, as this material is being stored in the vicinity of the SF7 crane.	3	C	M	Deck plan. MSDS. COSHH assessments.	Halliburton to supply SF7 with information on hazardous material types and quantities. Action Party: Neringa Dugnaite Date: 22/02/12	4	B	L	
4.0	**Well Handover**											
4.1	Well status prior to commencement of operations.	Well unsafe for intervention activities.	Potential for work to start on well that is not correctly isolated.	2	B	M	Well status document and isolation certificate will be prepared and passed over from ERT to Halliburton personnel. Well work will be undertaken under PTW system. Daily JSA / TBT will confirm ongoing status of wells.		1	A	L	
4.2	Transmission of well status documentation.	Document transmission facilities unavailable.	N/A, all transfer is undertaken offshore.	-	-	-						
5.0	**Well abandonment activities**											

5.1	Swab cap removal.	Trapped pressure below swab cap.	Release of pressure.	4	C	L	Pressure bleed off procedure.		4	B	L	
5.2	General hazards - adverse weather.	Fog. High winds. Lightning. Sea state.	Potential personnel injury due to adverse weather conditions. Schedule delay.	3	C	M	Weather monitoring / forecasts. Helicopter limits. ERRV support. Operating limits. Daily TBT.		3	B	L	
5.3	General hazards - vessel collision.	Supply boats. Passing shipping. Fishing / seismic vessels in the vicinity.	Potential damage to vessel / installations.	2	A	L	Vessel marine packages. ERRV monitoring.		2	A	L	
5.4	General hazards - heli-ops.	Helicopter collision with platform or SF7.	Personnel injury. Damage to installation.	1	A	L	Standard heli-ops procedures. Adverse weather limitations. Co-ordination of heli-ops by SF7.		1	A	L	
		Helicopter landing on Camelot CA helideck.	Personnel injury. Loss of helicopter, due to collision with abandonment equipment being stored on helideck.	1	A	L	Prior decommissioning of Camelot helideck (see entry 3.2 above). Notification to helicopter operators of unavailability of Camelot helideck for the duration of abandonment operations. Helideck marked with yellow cross on red background and reg flag with yellow cross flown.		1	A	L	
5.5	General hazards - working at height.	Fall from height. Dropped objects impacting personnel / equipment below.	Personnel injury, equipment damage.	2	B	M	Procedures to highlight operation as safety critical. **TBRA –** Working at Height.		2	A	L	
5.6	General hazards - chemicals handling.	Spillage of chemicals.	Potential health hazard to personnel. Release to the environment.	4	B	L	All chemicals supplied in approved labelled containers. COSHH handling procedures. PON permit agreed. Any variation to programme to reflect in PON permit. MSDS sheets to be forwarded to		4	A	L	

							vessel prior to mobilisation. Bunding on SF7 storage areas and on pumping skid.					
5.7	General hazards - explosives handling.	Storage of explosives: Detonation on deck. Premature detonation downhole. Lightning strike. Failure to detonate. Disposal of unexploded charges.	Personnel injury.	2	B	L	**TBRA** - Explosives Handling. Local safety rules. Explosives stored in UN certified container and are radio safe. Stored in designated area - expected to be on heli-deck on Camelot subject to approval. Detonators transported and stored separately from explosives. Safe area enforced when explosives being used. Last to be brought on board, first to be removed.		2	A	L	
5.8	Excess weight on heli-deck.	Storage of equipment on Camelot heli-deck.	Potential overload.	2	B	M	Weight limits being assessed by Atkins and will determine maximum allowable.		4	A	L	
5.9	General hazards - NORM.	NORM present on equipment / retrieved downhole equipment.	Potential for contamination of personnel.	4	B	L	**TBRA –** Check toolstrings for NORM. NORM procedures, quarantine area and equipment is available. NORM not previously encountered on Camelot CA but items to be checked for NORM prior to handling by competent person. RPS will be present.		4	A	L	
5.10	General hazards - dropped objects.	Refer to crane / skidding and lifting entries in Table 2.0 above.										
5.11	General hazards - communications.	During pulling operations when both cranes are being used.	Potential personnel injury, dropped objects.	3	A	L	Procedure to be finalised, but will require a single person to be in overall control of lifting operations during this critical phase.	Finalise HSE plan and procedure for tandem crane use for pulling tubing / silo movement.	3	A	L	

								Action Party: C Jones Date: 24/02/12				
5.12	General hazards lifting operations.	Use of Camelot / SF7 cranes in tandem	None, crane operations will not be undertaken simultaneously.	-	-	-	Lifting plans, with special co-ordination is required to ensure that crane operations are not undertaken out of phase.		-	-	-	
5.13	General hazards - evacuation.	Escape / evacuation of personnel in an emergency.	Personnel trapped on Camelot CA unable to use gangway connection.	4	A	L	ER drill/exercise. In emergency conditions, if personnel are unable to return to SF7 via the gangway, they are instructed to muster next to Camelot lifeboat. Camelot CA lifeboat remains available for use if return to SF7 is not available.	Check situation regarding big people in lifeboats with respect to the Camelot lifeboat. Action Party: G Falco Date: 24/02/12	4	A	L	
			Requirement to evacuate SF7.	4	A	L	SF7 lifeboats / rafts are used in accordance with ER procedures. SF7 personnel can evacuate to Camelot, but only in circumstances where lifeboat evacuation is not contemplated, e.g. impending ship collision.		4	A	L	
5.14	General hazards - rescue.	Man overboard. Medevac.	Personnel injury. Delay in effecting recovery / rescue.	2	B	M	Provision of ERRV. Stretcher is available for rescue of injured person. ERT ER Procedure to be followed.		2	A	L	
5.15	Set up equipment, function testing and operation of torque equipment.	Use of air lines. Existing pressure in equipment to be tightened / slackened. Chemical/fluid spills. Hose Failure. Ergonomics.	Injury to personnel. Damage to equipment through over tensioning.	2	B	M	Secure air lines with whip checks and R-pins. Bleed off pressure wherever possible prior to start. Flush through equipment prior to operations if appropriate. Certified and tested equipment,		2	A	L	

		Torque head failure.					inspected prior to use. Attempt to minimise over stretching or bad posture by moving or rotating equipment where possible. Pressure checks as per procedures. Correct hand placement, avoid one person operation, use 2 people and maintain good communications. Trained and competent personnel. Check settings i.e. ft/lbs or psi required prior to commencement. Equipment calibration.					
5.16	Set up – safe access / egress.	Blocking of escape / access routes.	Delayed escape / evacuation in an emergency.	2	B	M	Deck plans. Steps-ups provided as required on SF7. Station Bill modified to show primary muster on SF7 and secondary muster on Camelot.	Provide amended signage in line with Station Bill provisions. Action Party: G Falco Date: 24/02/12 Revise induction programme for personnel to reflect revised arrangements. Action Party: G Falco Date: 24/02/12	1	A	L	
5.17	Downhole Programme – Camelot CA.	Dropped objects. Manual Handling. Moving Loads.	Personnel injury, damage to equipment.	2	B	M	TRAC held prior to picking up toolstring. HALLIBURTON Slickline Risk Assessments Reference to be made to HALLIBURTON guidelines for slickline operations. Well cover/grating to be used during toolstring change out.		2	A	L	
5.18	Downhole Programme –	Inability to obtain required well isolations.	Schedule delay until required barriers are in place.	2	B	M	Single cement barrier in place. Seawater column provides		2	A	L	

	Camelot CA.						secondary barrier. Xmas tree remains in place until the above barriers are in place and tested. Well isolation requirements stated within well programme.					
		Loss of well isolation as programme progresses.	Wells are sub hydrostatic, so no flow to surface and no consequence identified, other than schedule delay.	3	B	L			3	B	L	
5.19	Slickline/Eline Ops.	Stuck tools in well. Wire breakage.	Schedule delay.	2	B	M	Reference to HALLIBURTON risk assessments. Toolstring recommended in programme and to be signed off by offshore project manager prior to RIH. Regular pickup weights to be taken. Tested and certified equipment. Communication via VHF radio & Inmarsat. **TBA -** Wireline Operations. IWOP exercise conducted prior to carrying out workscope. Specific procedure in WOPM for Slickline Operations in shallow water.		2	A	L	
5.20	Hydrate formation.	Stuck tools in well.	Schedule delay, but hydrates are not anticipated during operation.	3	B	L			3	B	L	
5.21	Toolstring Lengths.	Toolstring lengths affect ability to achieve barriers.	Schedule delay.	2	B	M	Lengths of toolstrings to be supplied along with checklist prior to RIH. Trained and competent personnel. Downhole programme review held onboard with all personnel (IWOP).		2	A	L	

							Toolstring lengths to be physically measured & witnessed by ERT. Toolstring Checklists to be completed prior to deployment.					
5.22	Downhole explosive cutting/punching ops.	Inadvertent / premature detonation on deck. Detonation in incorrect location.	Potential personnel injury due to inadvertent detonation on deck. Schedule delay.	2	B	M	Safety checks undertaken at surface. Use of safety key by qualified explosives operator. Explosives Certificate to be in place. Weather forecast will be used before agreement to arm is obtained (to guard against potential for lightning strikes).		2	A	L	
5.23	Cementing ops.	Dust generation. Potential for blockage of lines during cement bunkering.	Potential health hazard. Potential ingress of cement dust into SF7 HVAC systems.	4	B	L	Dust masks will be used. Hose configuration to avoid kinking or blockage.		4	A	L	
5.24	Pumping Operations.	Comms failure.	Requirement to suspend operations until comms are restored, schedule delay	4	A	L	Redundancy of comms provision Radio check to be carried out prior to ops commencing		4	A	L	
		Release of pressure. Equipment malfunction / failure. Over pressure of system.	Potential personnel injury / equipment damage.	2	B	M	PRV's included in surface rig up & valves open as per procedure. Confirm correct line up prior to pump being started. Certified equipment. All lines pressure tested prior to ops starting. Barriers & PA announcements given. Back up equipment is provided in case of failure. Additional lighting available if required. Slow pump rate initially. All non-essential personnel are instructed to leave the area.		2	A	L	

	Flushing of pumping equipment after use.	Discharge of cement to the environment.	Potential damage to SF7 jacking system from cement.	2	B	M	Provision of hoses long enough to reach sea.		4	A	L	
5.25	Leak from piping / equipment.	Loss of containment.	Spillage of OBM / chemicals onto platform decking. Discharge of fluids to sea. Restrictions in SF7 drain system.	2	B	M	All fluids contained within break tank. Bunding is provided for blender and pump. No contaminated wellbore fluids discharged to sea (sheen test to be carried out under authority of offshore project manager). PON 15 figures submitted. PON 15 chemical & fluids managed accordingly. Usage/discharge volumes monitored and reported daily. Gases are cold vented. Plugging of drains is possible on SF7 in the event that a spillage occurs to prevent damage / blockage.		4	A	L	
5.26	Venting through OBM slops tank on SF7.	Cold Venting. Hydrates.	No significant consequence, hydrocarbon inventories are minimal.	4	B	L	No contaminated wellbore fluid discharged to sea. Gases are cold vented. Wind direction and strength to be checked regularly.		4	A	L	
5.27	Flowline N2 purging.	Overpressuring of line, N2 release.	Potential asphyxiant risk. Personnel injury from pressure release.	3	B	L	Competent crews and use of certified and tested equipment. Procedures and use of PTW. Barriering off. Operation carried out in open air.		3	A	L	
5.28	Flowline and chemical injection line removal.	Heavy lift. Dropped object. Trapped pressure.	Personnel injury, damage to equipment. NORM / Asbestos contamination of personnel.	2	C	M	DO safeguards as above. NORM - as previous entry. Asbestos - quarantined on platform and returned for specialist		2	A	L	

		NORM. Asbestos (from gaskets)					disposal onshore, all as per procedures.					
5.29	Wing valve leakage.	Release of pressure.	Inability to complete pressure test.	3	B	M	None identified.	Provide blind flange, gaskets and bolts. Action: G Falco Date: 24/02/12	3	A	L	
5.30	Xmas tree removal.	Dropped / swinging load. Potential trapped pressure inside tree.	As previous for dropped objects / trapped pressure.	2	B	M	Lift cap provided. Functioning of valves, vent off procedures. Lift plan.		2	A	L	
5.31	Rig up of Tension Table.	Manual handling. Dropped objects. Working at Height over hatch.	Injury to personnel, damage to equipment.	2	B	M	Procedures. Lift plans.	Provide cover for top of tubing once tree removed. Action: G Falco Date: 24/02/12	2	A	L	
5.32	Rigging of scaffolding around Tension Table.	Fall from height.	Personnel injury. Schedule delay if insufficient scaffold materials available to scaffold all well slots.	1	B	M	Routine scaffolding operation. Survey by Cape already completed.		1	A	L	
5.33	Operation of Tension Table.	Slips, trips, falls. Burst hydraulic lines. Operation in a congested area. Working at height.	Personnel injury.	4	C	L	Operations procedures. Trained and competent personnel. Certified equipment. JSA / TBTs. Restricted number of personnel permitted on tension table.		4	B	L	
5.34	Handling Of Heavy Down-Hole Tooling.	Dropped Objects. Manual Handling. Moving Loads.	Potential personnel injury / equipment damage.	2	B	M	Manual handling training for all personnel. TRAC/TBT. Good communications/planning. Correct tools for the job. Planning of equipment positioning to assist handling.		2	A	L	

							HALLIBURTON Risk Assessments. Non essential personnel kept away from area.					
5.35	Use of elevators.	Equipment damage, pinch points/entrapment. Dropped objects/swinging loads. Failure of rigging. Weather. Loss of communications.	Potential personnel injury / equipment damage.	2	B	M	Certified equipment, barriers. Trained and competent personnel. Appropriate restraints provided. Dedicated banksman. Certified lifting equipment. Dedicated lifting points. Ability to use crane to ensure safe lift. TBT, PPE. Procedures. Any suspended loads contain certified lifting equipment. Slot covers to be closed where possible. Fall protection and tag lines. Certified equipment, inspect before use. Weather to be reviewed during TBT. Dedicated banksman. Agreed hand signals. All stop in place. Use of TRAC. Locking device to prevent bails from dropping. Clear above and below.		2	A	L	
5.36		SWL exceeded.	Equipment failure, personnel injury.	2	B	M		Provide 150 tonne elevators. Action Party: B Cooper Date: 24/02/12	2	A	L	
5.37	Incorrect load indication given	Over / under pull indicated.	Overpull may result in shock loading to crane.	2	B	M	Monitoring crane initial pick up weight against calculated tension		2	A	L	

	on crane.						table weight.					
5.38	Use of slips.	Dropped Objects. Manual Handling. Working at Height. Rigging Failure. Loss of Comms. Pinch points/entrapment.	Potential personnel injury / equipment damage.	2	B	M	Certified Rigging. Handrails are provided. Scaffold toe boards. Correct manual handling techniques. Permit to Work. Correct working at height PPE. Clear above and below. Check rigging prior to use. Certified rigging. Rigged by competent personnel. All covers over holes. Certified equipment. All stop until comms reinstated. Correct Hand placement. Correct manual handling techniques. Correct Hand placement. Correct PPE. Correct body placement. Clear above and below.		2	A	L	
5.39	Diesel bunkering on SF7.	Ignition sources from additional equipment on SF7 deck.	Fire, personnel injury.	3	B	L	SF 7 diesel bunker procedures prohibit hot work whilst offload is ongoing. Potential to load up on diesel in advance of abandonment operations starting (depending on weight limits not being exceeded).		3	A	L	
5.40	Use of power tong equipment.	Hydraulic leaks / pressure release. Pins not located.	Potential personnel injury / equipment damage.	2	B	M	Certified & serviced equipment to be used. Spill kit on site.		1	A	L	

		Entrapment. Slips, trips, falls. Collisions. Damage to Equipment. Pinch points. Broken DIE missile potential.					Area clear of non essential personnel. Competent operator and supervision. Ensure there is sufficient slack, and all snag points are removed. Use proper hose routing and monitored. Good communications. Positioning and awareness. Good housekeeping. Be aware of your surroundings. Equipment checked and ready for use. Proper placement of hands. Use only dedicated hand holds. Good communication. Use proper PPE for the job. Correct DIE placement.					
6.0	**Rig down / demobilisation**											
6.1	Waste disposal.	Spillage	Potential pollution.	2	B	M	Dedicated contractor for disposal. Communication between platform and supply boat. Demob Plan in place. Contractor to be made aware of tank volume and contents. Tote tank disposal is an option if supply boat unavailable. Transmission onshore under Dangerous Goods requirements and under guidance of specialist waste contractor.		2	A	L	