University of Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study program / Specialization: **Petroleum Engineering / Drilling Engineering**	Spring semester, 2018 Open
Author: **Airat Valeev**	……………………………………………… (signature of author)
Internal supervisor: **Mesfin Belayneh Agonafir** External supervisor: **Eva Malmanger,** Wintershall Norge AS	
Title of master's thesis: **Performance evaluation of subsea petroleum activities utilizing vessels**	
Credits (ECTS): 30	
Key words: Inspection maintenance and repair Light well interventions Subsea plug and abandonment Marine operations Optimization Vessels	Number of Pages: 97 + supplemental material/other 2 Stavanger, July 15 / 2018

Title Page for Master's Thesis

Faculty of Science and Technology

Acknowledgement

Firstly, I would like to express my gratitude to Eva Malmanger from Wintershall Norge. Her guidance and support throughout the working process helped me to complete this master thesis. Additionally, I would like to thank John Kåre Smistad, Sturle Bø Steinnes, Bård Lode Norheim and other colleagues from Wintershall for being patient and outgoing, while I was asking my numerous questions. Thank You for sharing with me your valuable experience. It was a pleasure for me to work with such a great people.

Secondly, I want to thank my supervisor at the University of Stavanger – Mesfin Belayneh Agonafir. He has provided me with assistance during the project and has given me valuable advice regarding the thesis. Moreover, my gratitude goes to Kris Ravi, who helped me to structure the work. Also, I would like to thank Morten Myhre from HydraWell for giving his time to talk to me and discuss some of my ideas. Special thanks to my friend Mels, who helped me to deal with pictures and modify them.

Finally, I wish to thank my parents, girlfriend, and friends for supporting me throughout the whole study process and especially during the last semester.

Airat Valeev

Abstract

Global consumption of the fossil fuels is continuously growing. The oil and gas industry is extending the frontiers of exploration and production towards challenging areas such as deep-water zones and arctic regions. Moreover, the industry is forced to improve recovery from the older fields. Therefore, the number of deep-water and subsea wells is increasing, and at the same time, the number of operations required to maintain these wells is growing as well.

Intervention and maintenance of subsea installations can be performed either with a rig or a vessel, depending on the complexity of the activity. However, rig interventions are far more expensive compared to the vessel based, and this supports the statement that marine operations should be performed mostly by vessels in the future and should be optimized by reducing the number of intervention days and development of new safe and cost-effective techniques. Based on the Norwegian Continental Shelf (NCS) history, company job reports and discussions with experts, the objective of the thesis is to determine which operational steps and processes of subsea activities can be improved, and how the downtime can be reduced. Additionally, the possibility of performing rigless plugging and abandonment (P&A) operations utilizing light well intervention vessel by implementing state-of-the-art techniques is evaluated.

My conclusion from the study shows that time spent on some operations might be reduced by checking and updating the procedures and optimization of some steps within light well intervention (LWI) and inspection, maintenance, and repair (IMR) activities. Also, this thesis proposes how different P&A phases can be performed without utilizing a rig. Recommendations and results are grouped into separate sections and presented at the end of each major chapter.

Table of Contents

List of figures

List of tables

Abbreviations

A	
ALVD	Acoustic leak and vibration detector
AoC	Acknowledgement of compliance
C	
CIV	Chemical injection valve
CM	Choke module
CMRT	Choke module running tool
CP	Cathodic protection
CT	Coiled tubing
D	
DP	Dynamic positioning
E	
ETC	External tree cap
F	
FAB	Formation as a barrier
FLAGS	Far North Liquids and Associated Gas System
FPSO	Floating production, storage and offloading unit
G	
GW	Guide wire
H	
HC	Hydrocarbon
HP	High pressure
HSE	Health safety and environment
I	
IMR	Inspection maintenance and repair
L	
LLP	Lower lubricator package
LWI	Light well intervention
M	
MEG	Mono ethylene glycol

N	
NCS	Norwegian continental shelf
NPD	Norwegian Petroleum Directorate
O	
OTS	Oseberg Transport System
P	
P&A	Plug and abandonment
PCH	Pressure control head
PLR	Pig launcher retriever
PLT	Production logging test
PSA	Petroleum Safety Authority of Norway
PWC	Perforate wash and cement
R	
RAIC	Radioactive isotope counter
RLWI	Riserless light well intervention
ROT	Remotely operated tool
ROV	Remotely operated vehicle
S	
SCM	Subsea control module
SD	Sand detector
SS	Subsea
T	
TA	Temporary abandonment
U	
ULP	Upper lubricator package
W	
WBE	Well barrier element
WCP	Well control package
WOW	Waiting-on-weather
WROV	Work remotely operated vehicle

1 Introduction

This master thesis describes the utilization and application of vessels in the petroleum industry regarding their performance (application, limitations, and optimization) during light well interventions (LWI), inspection maintenance and repair (IMR) activities, and plug and abandonment (P&A) operations. Based on field case studies, possible future opportunities in utilization and improvements are also discussed in this thesis.

1.1 Background

There are more than 5 000 subsea wells around the world, and this number is increasing every day because the industry is forced to explore cheaper development solutions due to depletion of shallow wells and conventional fields.

Production from some old subsea fields can have a positive trend due to improved oil recovery techniques. Evidence for this can be recent data from NPD (figure 1), where it is stated that production starts to raise and will demonstrate steady growth during next six years. [1]

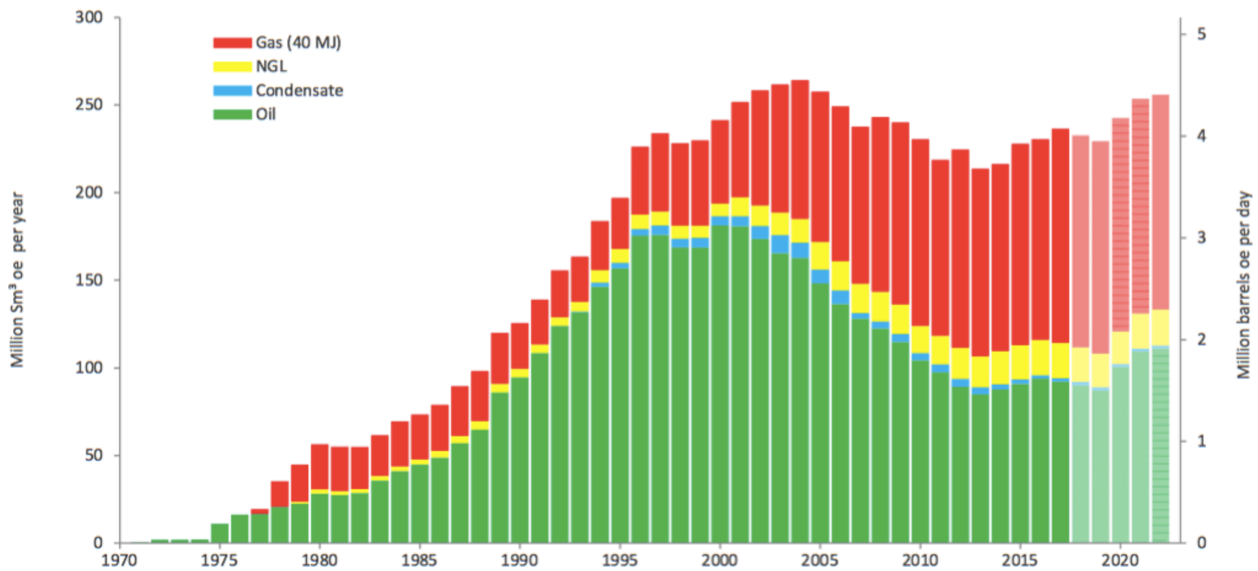


Figure 1 – NCS Oil and gas production timeline [1]

During the oil and gas production lifetime well intervention and maintenance activities will also be conducted more frequently and will generally be in demand. Such subsea petroleum activities were for a long time performed exclusively by semi-submersible, jack-up and other type rigs. However, this trend slightly changed during last twenty years due to cost and efficiency issues. Nowadays, light well interventions become more and more common, due to a lower daily rate of a vessel compared to a rig, and sometimes due to a higher operational efficiency of vessels. Even though LWI vessels, or multi-service vessels, cannot perform some certain operations related to interventions or plug and abandonment activities, the current technological aim of the whole offshore industry is to develop such intervention, and P&A techniques that will be applicable from a vessel and will minimize (and subsequently eliminate) rig utilization.

The Petroleum Safety Authority of Norway also supports this trend. According to recent assertions, “it is useful and important for the Norwegian shelf to gain further experience in light well intervention, and thus contribute to laying a foundation for more long-term solutions”. [2] Therefore, several research initiatives are dedicated to this area, to improve understanding of light well intervention services for subsea wells. This thesis work aims to study application, challenges and future opportunities of LWI/IMR in the petroleum industry.

1.2 Problem statement

Utilization of vessels in the oil and gas industry helps to minimize operational expenses compared to conventional rig-based activities and to increase efficiency. However, there are still lots of limitations, and unresolved areas of vessel usage due to different reasons. This master thesis addresses the following issues:

- Are there possible improvements in vessels performance?
- What are future opportunities of vessel utilization?

1.3 Objective

The main objective of the thesis is to answer questions mentioned above. To be precise, primary activities of the work include:

- Based on the analysis of subsea petroleum operations dataset:
    - Determine general and specific operational challenges

    - Determine possible solutions for optimization and state the recommendations
- For the most frequent and standard activities create operational benchmarks
- Assess the opportunities of performing plug and abandonment procedures utilizing vessels with the objective of cost reduction
- Indicate general trends in the subsea petroleum industry, IMR and LWI vessel construction and utilization, and P&A activities

1.4 Thesis structure

In this thesis work, three major groups of subsea petroleum activities are considered and studied. The first group of activities deals with well interventions. The second group encompasses the scope of IMR activities (inspection, maintenance, and repair of the subsea facilities). The third group of activities is dedicated to plugging and abandonment operations.

The master thesis includes 7 central chapters, which consist of smaller subchapters and sections. To create an impression of the structure and be aware of what to expect from the thesis, a brief overview of every main chapter is provided below:

- Chapter 1 includes a background part, objectives of the work and framework of the master thesis.
- Chapter 2 introduces Wintershall, which is an operating company that provides internal information on subsea activities and assistance to the thesis work.
- Chapter 3 presents a literature review, which describes subsea petroleum activities (well interventions, maintenance of subsea facilities and subsea P&A) and provides an overview of the offshore units in the petroleum industry, with the focus on LWI and IMR vessels.
- Chapter 4 gives an overview of maintenance operations performed on one of the North Sea fields and addresses recommendations for improvement of these operations.
- Chapter 5 indicates LWI activities performed by Wintershall and ends up with recommendations for their optimization.

- Chapter 6 starts with describing the challenges of subsea plug and abandonment procedure, followed by possible solutions, and continues with proposed changes and improvements into conventional P&A plan.
- Chapter 7 summarizes main ideas and proposed recommendations of the paper and provides an overall conclusion.

2 Mentoring company overview

The main part of the thesis was produced with the help of Wintershall. Therefore, before moving on to the topic, it is essential to give some information about the mentoring company. Information regarding the activities of the company, operating fields, and future projects are presented in the following chapter.

2.1 General information

Wintershall is the largest crude oil and natural gas producer in Germany, operating in over than 40 countries within these core regions: Europe, North Africa, South America, Russia, the Caspian Sea and the Middle East. In last years, Wintershall has continued to expand activities in Norway. Today local branch Wintershall Norge holds around 60 licenses on the Norwegian Continental Shelf and more than half of them as an operator (figure 2). The company is, therefore, one of the largest license holders in Norway, and invested approximately half of its global exploration budget in this region in 2016. [3]

Recent discoveries became one of the critical factors for growth of the company. One of them was the Maria field, which was discovered in 2010 and has an estimated 180 million barrels of oil equivalent of recoverable resources, another valuable discovery was the Nova field, where the development is going to start in 2018/2019. Among others operating fields, there is Brage and Vega.

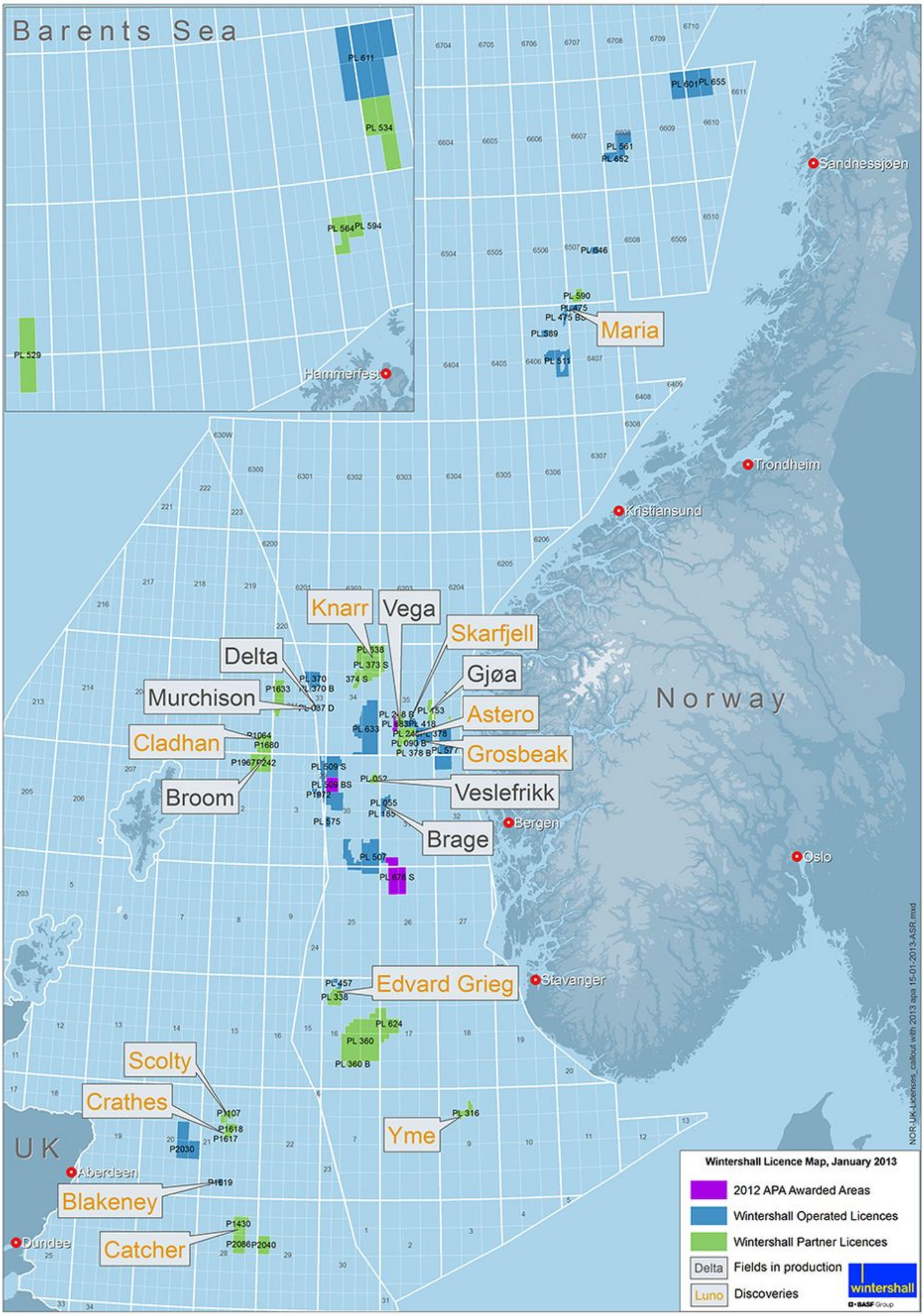


Figure 2 – Wintershall Norge licence map [3]

2.2 Major operating fields

2.2.1 Brage

Brage field is the first operated production field by Norwegian branch of Wintershall. The field is located to the east of Oseberg in the northern part of the North Sea, 125 kilometers west of Bergen (figure 3). Brage produces oil from sandstone of Early Jurassic age in the Statfjord Group, and sandstone of Middle Jurassic age in the Brent Group and the Fensfjord Formation. The reservoirs lie at a depth of 2 000 – 2 300 meters and water depth is 137 meters. The primary drainage strategy is water injection for oil-bearing formations for pressure support.

Figure 3 – Brage platform location [3]

Brage is a fully integrated steel jacket platform (figure 4) with living quarter, auxiliary equipment module, process module, drilling modules, well and manifold areas. [3]

Figure 4 – Brage platform [3]

Brage has no storage capacity, and oil is therefore exported via the Oseberg Transport System (OTS) to the Sture terminal. Produced gas is exported via a pipeline to Kårstø. [3]

2.2.2 Vega

Vega field is situated on the Northern part of the North Sea, 28 kilometers west of the Gjøa facility, 80 kilometers west of Florø. The field is a subsea tie-back to the Neptune operated Gjøa platform. Wintershall Norge took over the operatorship of the Vega field from Statoil (now Equinor) in March 2015. The field produces gas and condensate from Middle Jurassic shallow marine sandstone in the Brent Group. Vega South has an oil zone and is produced by pressure depletion with the underlying gas reservoir, providing natural gas lift. The reservoirs lie at a depth of 3 500 meters. [3]

Vega consists of three seabed templates. The well stream is sent by pipeline to the Gjøa platform for processing. Oil and condensate are transported from Gjøa in a pipeline tied to the Troll Oil Pipeline II for further transport to the Mongstad terminal as it is shown on figure 5. The rich gas is exported via pipeline to Far North Liquids and Associated Gas System (FLAGS) on the British continental shelf for further transport to St Fergus in the UK. [4]

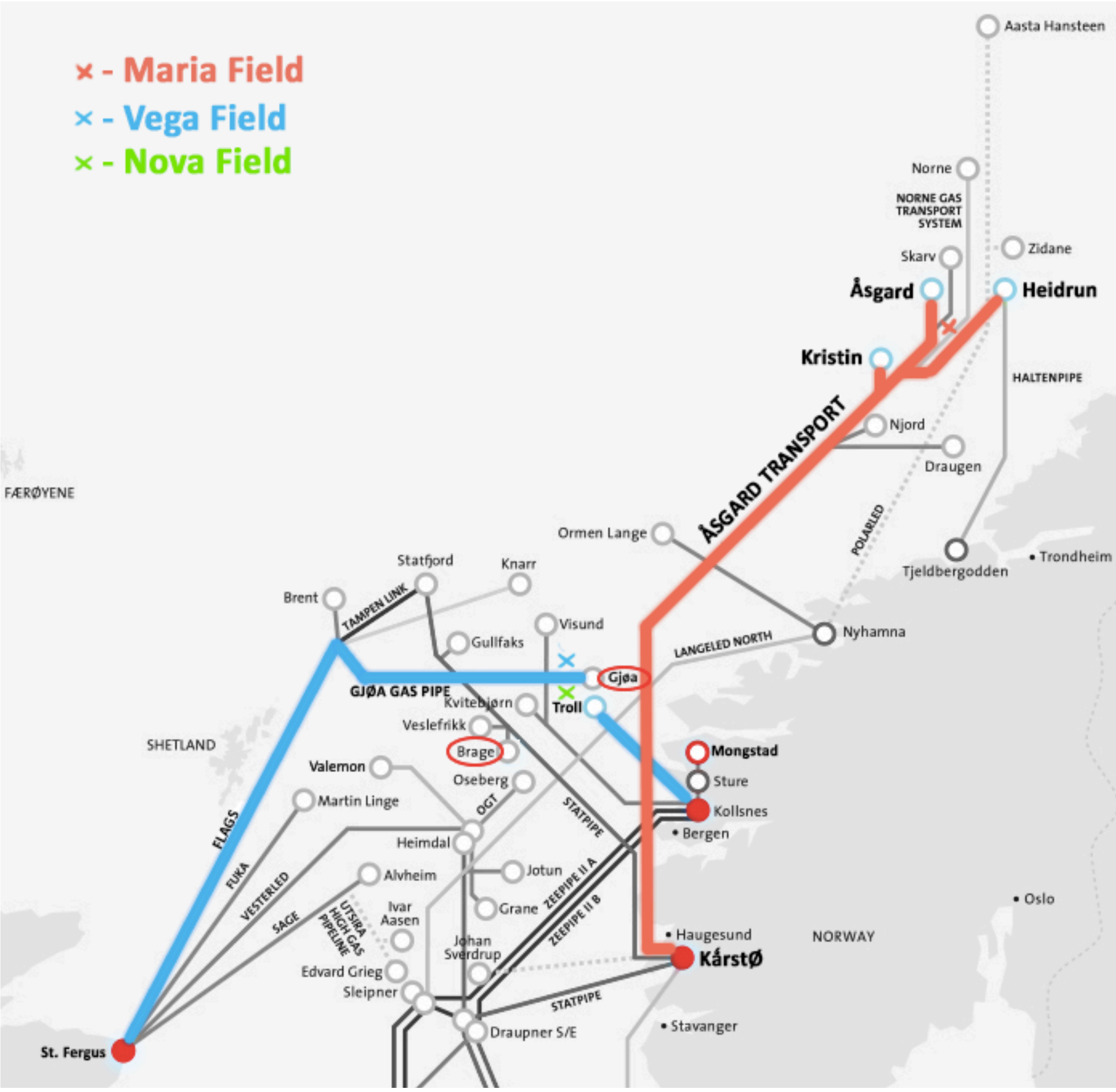


Figure 5 – NCS pipeline transportation system [5]

2.2.3 Maria

Maria is the first own-operated field in Norway, which Wintershall takes all the way from exploration, through development, and to production. The field is located at the Haltenbanken area of the southern Norwegian Sea, around 200 kilometers from the mainland. Maria produces oil and gas from the Middle Jurassic Garn Formation. The formation is 90 – 100 meters thick and consists of massive sandstone with shale layers. The reservoir lies at a depth of 3 800 meters.

The subsea production system consists of two 4-slot templates (figure 6). The templates are combined, and Maria has five producers and two water injectors in total.

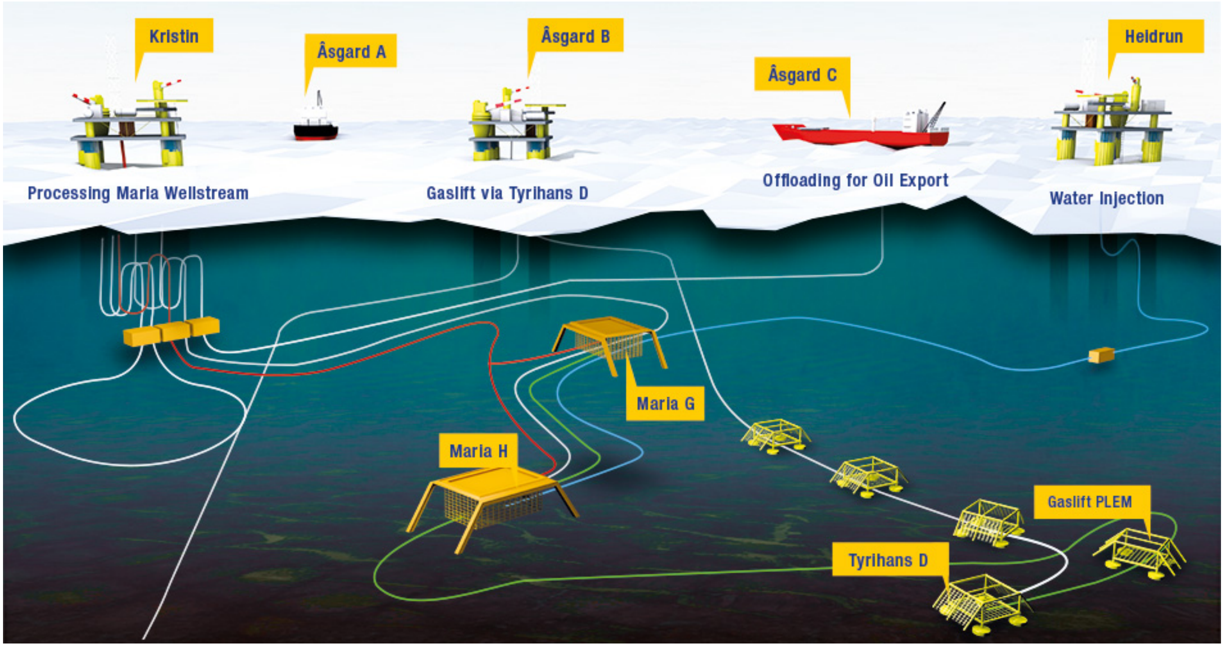


Figure 6 – Maria field templates layout and tie-back facilities [3]

The field is linked to 4 Equinor-operated hosts: Kristin, Heidrun, Tyrihans and Åsgard B platforms. Maria well stream goes to the Kristin platform for processing. Processed oil is sent to the Åsgard C field for storage and offloading to shuttle tankers. Gas is exported via the Åsgard Transport System to Kårstø. Detailed paths of the media from the field are depicted on figure 5. Water injection comes from Heidrun, and well gas lift comes from Åsgard B via Tyrihans. [3]

2.2.4 Nova

Nova (formerly known as Skarfjell) is an oil discovery located in the northeastern North Sea, around 16 kilometers south-west of the Gjøa field (figure 7). The Upper Jurassic reservoir sand is of an excellent quality containing light oil with a significant oil column underlying a gas cap. The expected recoverable reserves are estimated to 80 million barrels of oil equivalents.

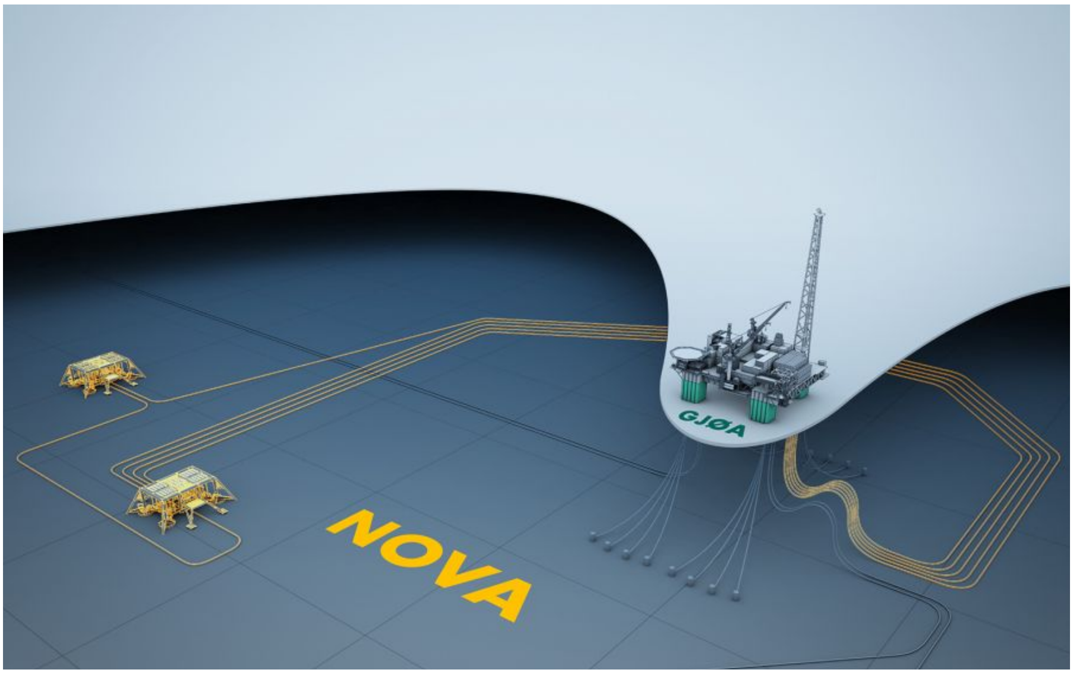


Figure 7 – Nova field [3]

Based on the proposed plan, hydrocarbons from the Nova reservoir will be developed via two subsea templates tied back to the Gjøa platform (figure 7) for processing and export. Gjøa will also provide water injection for pressure support. One template will be used for water injection, while the other will be used to produce hydrocarbons. [3]

In the second quarter of 2018, there was submitted a plan for the development of the field. Which means that the construction of subsea facilities has already started.

3 Subsea field activities

The age of subsea wells is growing, resulting in the necessity of well interventions to maintain well conditions and increase reservoir recovery. Moreover, other production facilities (i.e. pipelines, templates, manifolds) need to be regularly maintained. Finally, by the end of the field lifecycle, wells are to be plugged and abandoned. Therefore, three huge areas of subsea petroleum activities dedicated to the sustainable production and safe reservoir abandonment – IMR work, well intervention work and P&A – will be discussed in this chapter.

3.1 Well interventions

3.1.1 Definition and classification

A subsea well intervention (well work) is an operation carried out on a well during, or at the end of, its productive life that alters the state of the well or well geometry as well as provides well diagnostics and manages the production of the well. [5]

Well intervention work can be classified as heavy and light well interventions. Heavy interventions require the mobilization of a rig, while light interventions can be performed from LWI vessel. Such vessels are also known as Category A units and typically with wireline and sometimes coiled tubing on board to perform light interventions. [6]

Heavy interventions are performed by Category B and Category C units, or in other words, by workover or drilling rigs because they have a capability to pull the tubing. Figure 8 demonstrates this division into categories. Both heavy and light interventions require pressure control equipment to be installed on the well to perform work. It is also important to notice that the heavier the intervention is, the higher is the cost of operation. That is the driver for implementing technologies which will minimize rig usage.

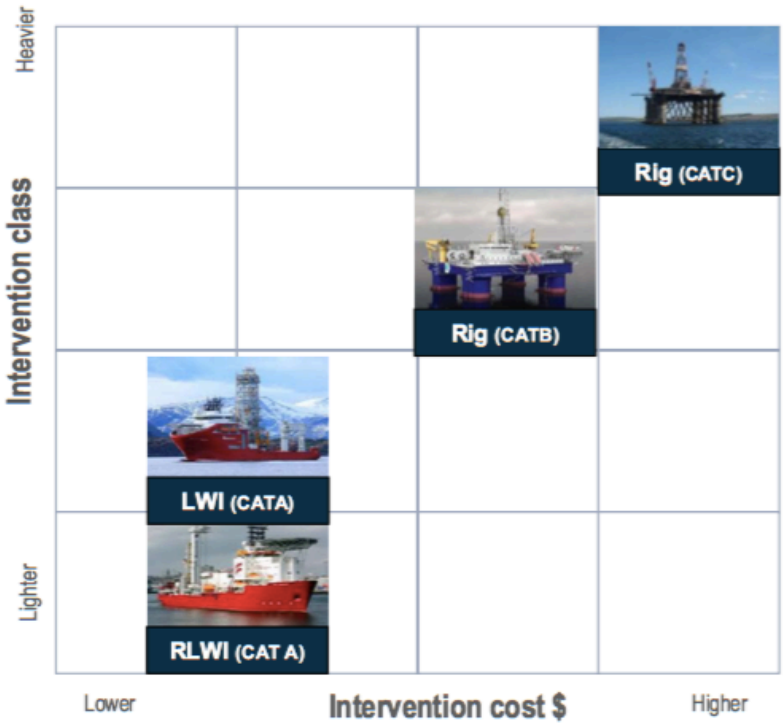


Figure 8 – Intervention classification [8]

In some cases, it is impossible to indicate the exact "border" between heavy and light interventions. Therefore, the term "medium interventions" sometimes occurs in the literature. However, it might take some time till vessels will develop and we can introduce a new type of intervention, or another possible scenario is that vessels will develop so much that the whole scope of interventions would be considered as light interventions. [8]

3.1.2 Light well intervention methods

In most cases intervention methods are divided into four major groups:

- Pumping
- Wireline
- Coiled Tubing (CT)
- Riser based

It is also important to note that pumping and wireline are considered as two main conveyance methods, because they do not require a riser system, and have proven to be effective for their application area. Riser-based LWI and CT interventions are performed less frequently due to high technical requirements from a vessel and necessary equipment is neither readily available in many cases.

Each of the groups has its own subgroups which will be indicated and explained briefly in this chapter.

3.1.2.1 Pumping

Pumping is a basic intervention method since it is not necessary to place any equipment directly inside the well while intervention is in progress (figure 9). Normally pumping is performed to prevent scale and hydrates accumulation in a well by pumping inhibitors, or to perform an acid job at the wellbore face. Other aims of pumping might be killing the well, or lifting operations. [7]

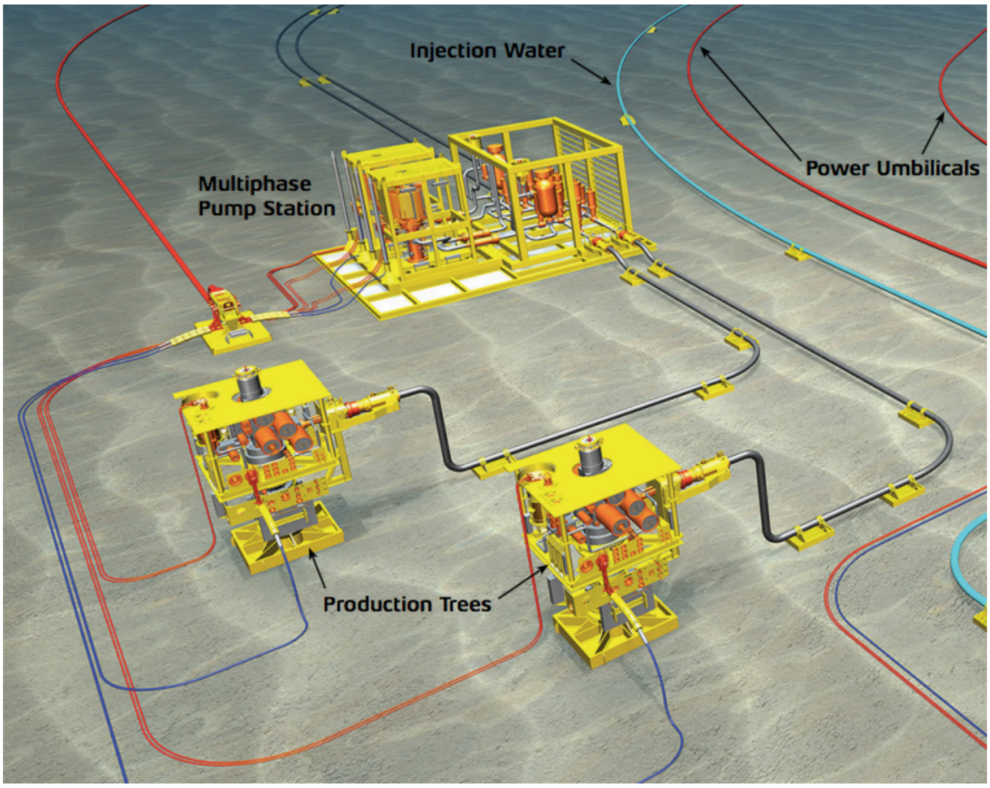


Figure 9 – Subsea pumping facilities [7]

Pumping jobs in subsea treatment are often performed as bullheading jobs since LWI subsea well interventions normally do not allow to circulate in and out return passages.

Other, but less common, ways of pumping application are:

- Diagnostics

- Tracer injection
- Washing (i.e. cleaning lower completion, jet cleaning)
- Formation damage

3.1.2.2 Wireline

Wireline is a general term that stands for the cabling technology used to lower down and lift the equipment in a well by a powered winch. Wireline unit does not require any specific additional installations, so it can be easily placed on a vessel as well as on a rig. There are three different types of cabling systems:

- Slick-line
- Braided line
- Electric line (or E-line)

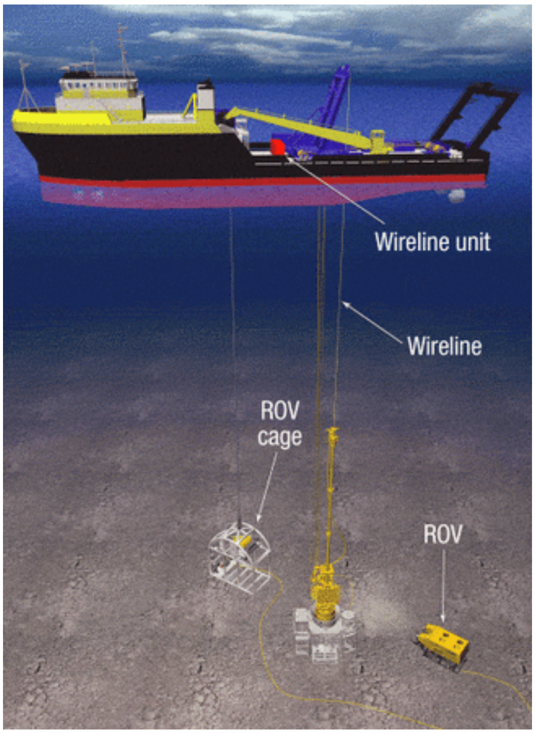


Figure 10 – Subsea wireline intervention system [11]

Slick-line is a method of conveying intervention tools into a well with the typically used steels wire diameter of 7/64 and 1/8 inches. Most tools used in the slick-line are mechanically driven.

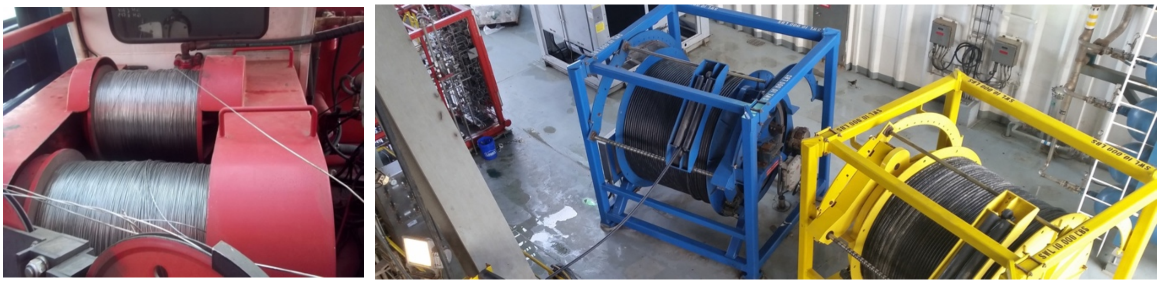


Figure 11 – Slickline unit [12]

Regular slick-line usage can be listed as [12]:

- Fishing (recovering items which are left or lost in the well)
- Cleaning well (i.e. debris removal)
- Pulling, running and operating of flow control devices
- Setting and removing plugs

Advantages	**Disadvantages**
Quick rig-up/rig-down	No real-time surface readout
Low cost	Limited wire strength
Small footprint	Lack of ability to circulate fluids downhole

Table 1 – Pros and cons of slickline [10]

Braided line is a heavier and stronger version of slick-line. This is achieved by braiding together strands of wires in different ways. Common diameter of braided line is 3/16 inches, although special heavy applications use 1/4 and 5/16 inches. This type of cable is used for heavy fishing operations, where slick-line does not have sufficient tensile strength. Advantages and disadvantages are similar to regular slick-line. [10]

Electric line (figure 12) is basically a braided line with an electrical cable in the middle to transmit real time data (i.e. real-time logging). Such cable can be used in highly deviated wells and ensures good depth control. However, it is more complex to rig-up e-line and costs are higher compared with traditional wireline cables. [10]

Figure 12 – Electric line example [10]

Typical wireline jobs can be summarized to [13]:

- Logging
- Plugging and setting packers
- (Re)perforating
- Drift runs
- Setting and pulling mechanical components
- Open and close sliding sleeves
- Fishing operations
- Scale removal
- Patching (to record a seismic trace)

3.1.2.3 Coiled tubing

Coiled tubing (CT) is a continuous tubing that is coiled around a big reel and without a need to make connections. The diameter of a tubing string is smaller than the diameter of a conventional drill pipe, therefore it is weaker. In the North Sea, a reel containing 5 000 m pipe of 1 ¾ - 2 3/8 inches in diameter is typically used (figure 13). [10]

CT opens the possibility to circulate fluids at relatively slow rates but the tubing itself cannot tolerate much torque and rotate. On the other hand, this challenge is overcomed by installing motors at the bottom of the coil to enable rotation of tools by pumping fluids. [12]

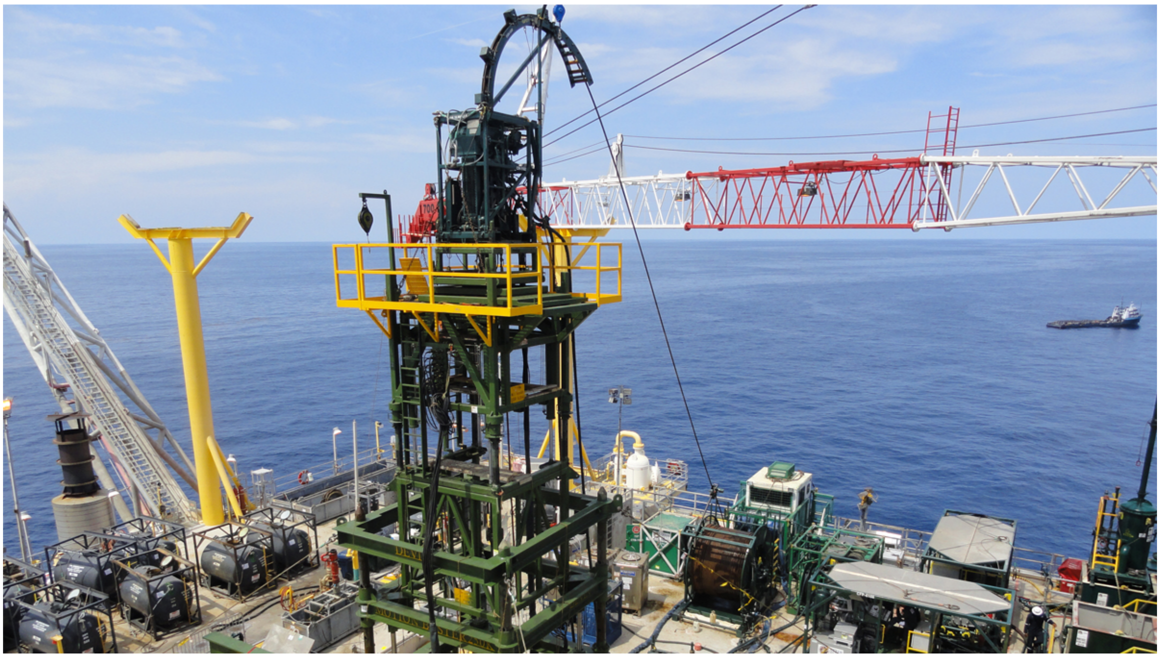


Figure 13 – Devin coiled tubing unit [14]

Challenges related to the coiled tubing are fatigue of the tubing itself and limited lifespan of a coil. The bend-cycle fatigue is higher on offshore operations performed from vessels with heave compensating systems. There are several typical mechanical damages which CT is subjected to [15]:

- Internal pressure loading
- Compressive axial forces
- Corrosion
- Torsional forces
- Mechanical damage

Another challenge is that the coiled tubing unit is heavy and requires considerable deck space and lifting capacity offshore. Therefore, not all vessels can fit such a unit and use this intervention method. These and other disadvantages of technology are provided in table 2.

CT applications and jobs include [10]:

- Cleanout
- Perforating
- Logging (when wireline is not applicable)
- Acidizing and stimulation

- Injections
- Cementing
- Milling

Advantages	Disadvantages
Stronger than a wireline	Heavy and requires much space and lifting capacity
Ability to operate in live wells with pressure at the surface	Subjected to fatigues and different types of loads
Cost effective	Short lifetime
Fluid circulation	Limited pumping capability

Table 2 – Pros and cons of coiled tubing unit [10]

3.1.2.4 Riser based light interventions

For deep intervention work, or for some of the coiled tubing intervention operations, a rigid riser is required to link an intervention vessel and a subsea Xmas tree. Such riser systems are not commonly presented on LWI vessels, because, usually for such workover operations rig is mobilized. However, there are some vessels (i.e. Well Enhancer by Helix) that can carry all mentioned above equipment and perform the large scope of intervention work except some heavy interventions which are [12]:

- High pressure snubbing (pipe is forced into a well against pressure; an operation performed in a live well when CT is not strong enough).
- Major workover (implies pulling out the production tubing for repair).

Generally, riser based interventions performed from a vessel are cheaper than those operations performed from a rig, however, well interventions performed from riserless vessels (RLWI vessel) seem to be a preferable prospect. Other pros and cons of riser based intervention method are stated in the table 3.

Advantages	Disadvantages
Ability to circulate and rotate	Long preparation time
Wide range of applications	Complexity of pressure control

Table 3 – Pros and cons of riser based intervention

3.1.3 Scope of intervention work

Throughout the life of a well, a number of planned or unplanned well interventions may arise and be required. Activities may include diagnostics, stimulation, surveillance, manipulation of equipment and repair of mechanical failure. The following identifies potential subsea intervention activities, that can be accommodated from an LWI vessel:

- Repairing of mechanical failures (downhole and in Xmas trees)
- Flow assurance operations
- Reservoir monitoring
- Well management activities (i.e. stimulation, injection)
- Recovering of wellhead, conductor and guide base

Within each group, there are lots of reasons to intervene the well, and such causes are presented in figure 14.

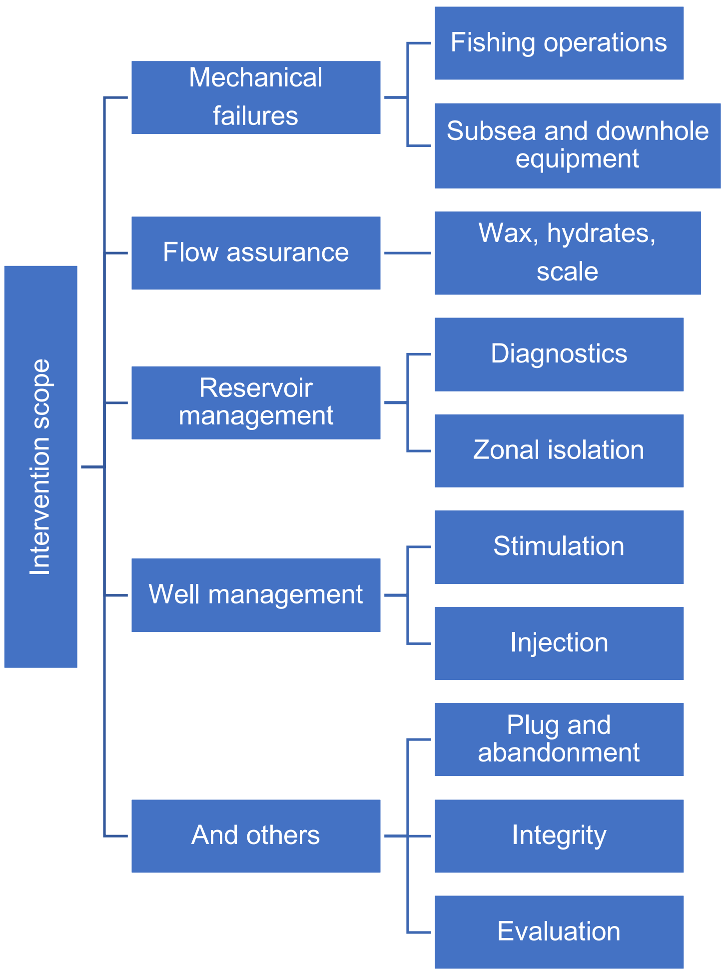


Figure 14 – Scope of intervention work

3.1.3.1 Mechanical failures

Different mechanical failures inside the well or failures of downhole and subsea equipment during the production stage is a reason why well intervention operations should be performed. Failures do not occur very often, but they require a big amount of time and money to be fixed.

3.1.3.2 Flow assurance

Another group of interventions is related to flow assurance problems. It is always important to monitor temperature and pressure in the tubing to control and subsequently prevent wax deposition, hydrates formation, scale accumulation etc. For instance, sometimes during shut-in situations, it is impossible to stop processes of unwanted elements deposition, and therefore, well interventions such as chemical treatment, mechanical scale removal, pumping inhibitors are performed.

3.1.3.3 Integrity

Integrity issues in most cases can be prevented by proper and up-to-date maintenance of the equipment. These activities can include barrier verification, pressure testing, plug setting and recent leak detection. Example of the operation of plug installation is going to be described in one of the next chapters.

3.1.3.4 Reservoir and well management

Well intervention activities related to well management are an essential part of the production process in general. Almost every well needs to be stimulated to increase recovery rates. These operations are also followed by reservoir management activities, which imply reservoir diagnostics, isolation of water zones and pressure measurement.

3.1.3.5 Well abandonment

At the end of life cycle, well should be intervened to be plugged and abandoned. Challenges occur when P&A is performed on subsea wells. The detailed overview of well intervention activities during P&A operation will be presented in chapter 6.

3.2 IMR activities

Before the description of IMR activities, it should be pointed out, that there is a difference between IMR and LWI operations concerning the regulations, because LWI activities on the NCS are supervised and regulated by Petroleum Safety Authority of Norway (PSA), while IMR activities are subjected to marine regulations.

3.2.1 Definition

IMR is an abbreviation for inspection, maintenance and repair, and IMR activities belong to one of this groups. Generally, IMR is dedicated to reaching sustainable production asset performance during life of a field and integrity.

Typical IMR vessel (figure 15) usually can perform these operations. However, sometimes additional equipment should be installed on a vessel for better performance (i.e. additional crane).

Figure 15 – IMR vessel "Seven Viking" [13]

3.2.2 Operations

Typical scope of IMR operations includes the following activities [16]:

- Scale squeeze operations
- Remotely operated tool operations
- Maintenance of subsea systems
- Subsea repair
- Commissioning
- Work ROV activities
- Pipeline, riser and cable inspection

3.2.2.1 Scale squeeze operations

Purpose of a scale squeeze operation is to dissolve scale and remove its unwanted build-up inside the production tubing in a subsea well to increase the oil production. That is done by injecting chemicals via a high pressure flexible hose into a well from a pump located on the board of a vessel. [17]

3.2.2.2 Structural inspection

Structural inspections are performed on subsea structures, offloading systems, risers and umbilicals, platforms and FPSOs. These inspections are done to evaluate conditions of a structure and to check leakages, damages and other defects.

3.2.2.3 Remotely operated tool operations

The purpose of ROT operations is to replace modules that can be changed on a subsea well or a structure. Typical modules are subsea control modules, choke bridges, flow control modules, choke modules, subsea pumps, flying leads, pull-in and tie-in tools. [17]

3.2.2.4 Maintenance of subsea systems

Maintenance of SS systems can include following services [17]:

- Module replacement
- Anode/cathode measurements and protection replacement
- Remedial burial of cables and pipelines
- Removal of foreign objects

- Dredging operations
- Mattress laying
- Free span rectification

3.2.2.5 Subsea repair operations

Such repair operations are usually performed inspections and might include spool replacement, clamp installation and cutting operations, and these can be also generally named as pipeline and cable repair.

3.2.2.6 Work ROV operations (WROV)

Remotely operated vehicles work encompasses a large scope of operations from rough operations with huge blocks and modules to finger-tip and accurate work with details at a great depth.

Figure 16 – Subsea work ROV [17]

Typical WROV operations include [17]:

- Cleaning and high pressure water jetting
- Inspection and survey
- Hatch operations on subsea structures and valve stations
- CP measurements of structures and pipes
- Cutting operations
- Handling of rigging equipment

- Electrical fault finding and hydraulic leak detection
- Valve operations
- Replacement of flying leads, jumpers and cables
- Replacement of sensors and meters
- Support during ROT operations

3.2.2.8 Cable inspection

Cable inspection implies that the cable burial depth is monitored over time and this is tracked alongside the cable electrical testing properties and general site seabed movement monitoring. [17]

3.3 Plug and abandonment activities

P&A activities are also considered as subsea petroleum operations and mainly combine several well intervention operations aiming to temporarily or permanently plug and abandon the well. Even though in most cases subsea P&A is done by a semi-submersible rig, vessels are also used for preparatory work and during the last stages.

3.3.1 Definition and classification

Abandonment implies forming a combination of well barriers to prevent any flow of media from the potential source of inflow. According to NORSOK D-10 well barrier itself is an envelope of one or several well barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation or to the external environment. Consequently, well barrier element is a physical element, which does not prevent flow itself, but in combination with other WBEs forms a well barrier. [19]

Based on the classification of P&A operations by purpose and period of abandonment, there can be highlighted four major types [19]:

- Suspension – well is subjected to construction or intervention (may need to be suspended without removing the well control equipment).

- Temporary abandoned (TA) – status where the well has been abandoned and the well control equipment is removed with the intention of later re-entry or permanent abandonment.
    - TA well with monitoring – no maximum abandonment period
    - TA well without monitoring – maximum abandonment period is three years
- Permanent abandonment – status where the well or part of the well, has been permanently plugged and abandoned without any current intention to be re-used or re-entered.
- Permanent abandonment of a section (sidetrack, slot recovery) – implies construction of a new wellbore with a new target.

3.3.2 P&A sequence

Within each type of abandonment, an operational sequence can differ. However, when we are talking about temporary or permanent abandonment, the whole activity is usually divided into four phases, which are [20]:

- Preparatory work/Phase 0 (*Pre-P&A Operations*)
    - clean the well and perform logging;
    - run and test plugs.
- Phase I (*Reservoir Abandonment*)
    - isolation of producing and injection zones by setting primary and secondary barriers;
    - tubing left in place or partly/fully retrieved.
- Phase II (*Intermediate Abandonment*)
    - isolating liners and milling operations;
    - setting intermediate plug.
- Phase III (*Wellhead and Conductor Removal*)
    - retrieval of wellhead and conductor;
    - shallow cuts of casing string;
    - cement filling of craters.

There will be provided a more detailed explanation of each phase in chapter 6. It is important to note, that preparatory work and phase III might be conducted by a LWI vessel.

3.4 Offshore units

The main idea of the section is to indicate the classification of vessels and offshore units, which can perform a range of operations mentioned in previous chapters.

However, prior to focus on LWI and IMR vessels, it will be useful to briefly touch all types of offshore ships, which used by industry today. They can be mainly classified into the following main groups [21]:

- Oil exploration and drilling vessels
- Offshore support vessels
- Offshore production vessels
- Construction/special purpose vessels

Each of this category comprises a variety of vessels.

3.4.1 LWI and IMR vessels

LWI and IMR vessels are both highly technical vessels and can perform a wide range of operations. They are equipped with a dynamic positioning system and usually have a large deck area, which is used for the carriage of auxiliary equipment. Most vessels have a crane for supplies and installation of small-size structures. All vessels have a moon pool installed for the support of ROVs. Length of a vessel varies between 100 and 140 meters. The modern design of a vessel allows operating in the harshest weather conditions, including the arctic environment. Many new vessels have an ice-class notation and carry winterization equipment. Newer vessels are designed to be environmentally friendly and energy efficient by reducing emissions, using less or alternative fuel (i.e. LNG) and noise reduction.

There is a number of differences between a typical LWI vessel and a typical IMR vessel, especially under Norwegian regulations. Table 4 indicates these differences.

Difference	LWI vessel (figure 17)	IMR vessel (figure 18)
Design	Bigger deck space (allowing allocation of different advanced equipment)	Smaller deck space area
Dynamic positioning class	DP III (explanation is presented in Appendix A)	DP II or less
Operations	LWI activities: • Light well intervention services and associated work • Construction work • Subsea installation work • Securing of wells • Trenching and crane work • P&A work • Tower and module handling • Supply duties + IMR work	IMR activities (from section 3.2) • Structural inspections • Cable inspection • Remotely operated tool operation • WROV interventions • Module handling operations • Scale squeeze • Maintenance and repair of subsea systems • Pipe and cable repair • Light construction and commissioning operations
Regulations	Performs petroleum activities and, therefore, a unit must have an acknowledgement of compliance (AoC)	Performs operations under marine regulations, and do not need to have an AoC
Equipment	Can have a heave-compensating derrick and a coiled tubing unit, in addition to wireline tools (figure 17)	Usually have main and auxiliary cranes and module handling system (figure 18)

Table 4 – Difference between IMR and LWI vessels

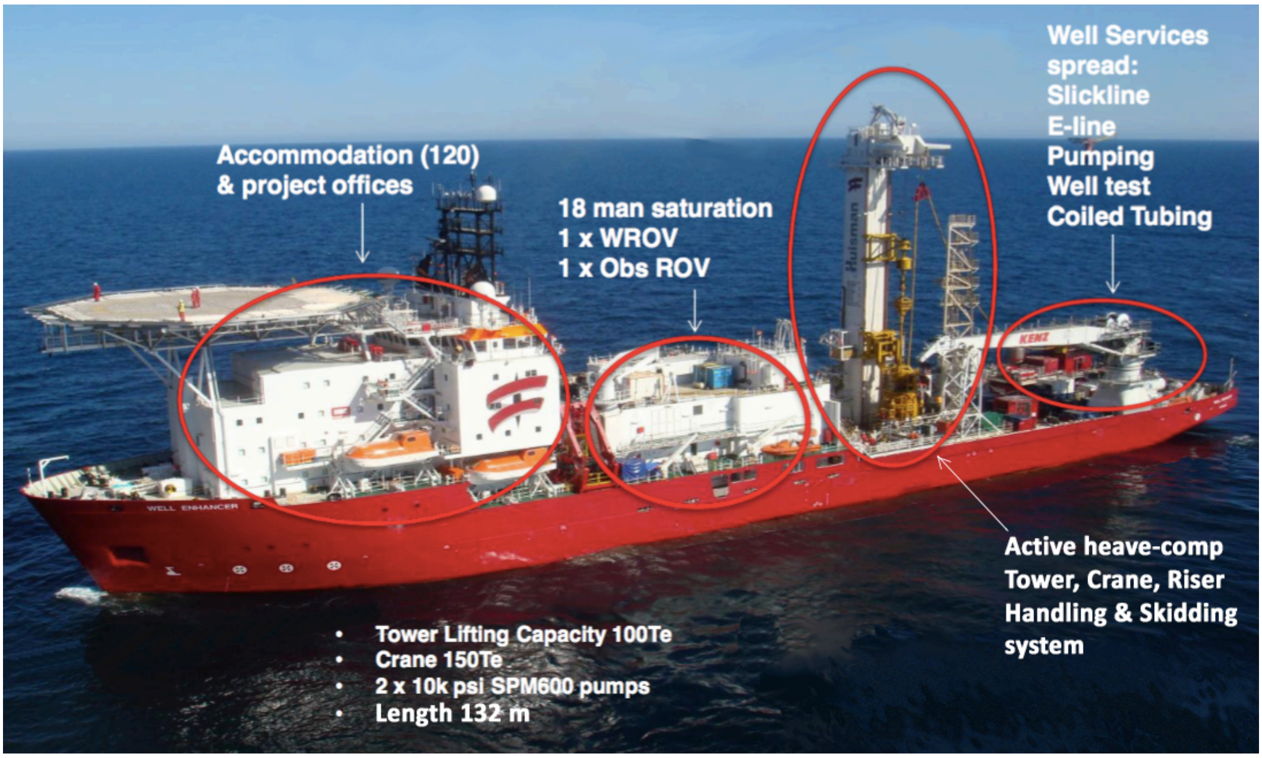


Figure 17 – LWI vessel "Well Enhancer" [22]

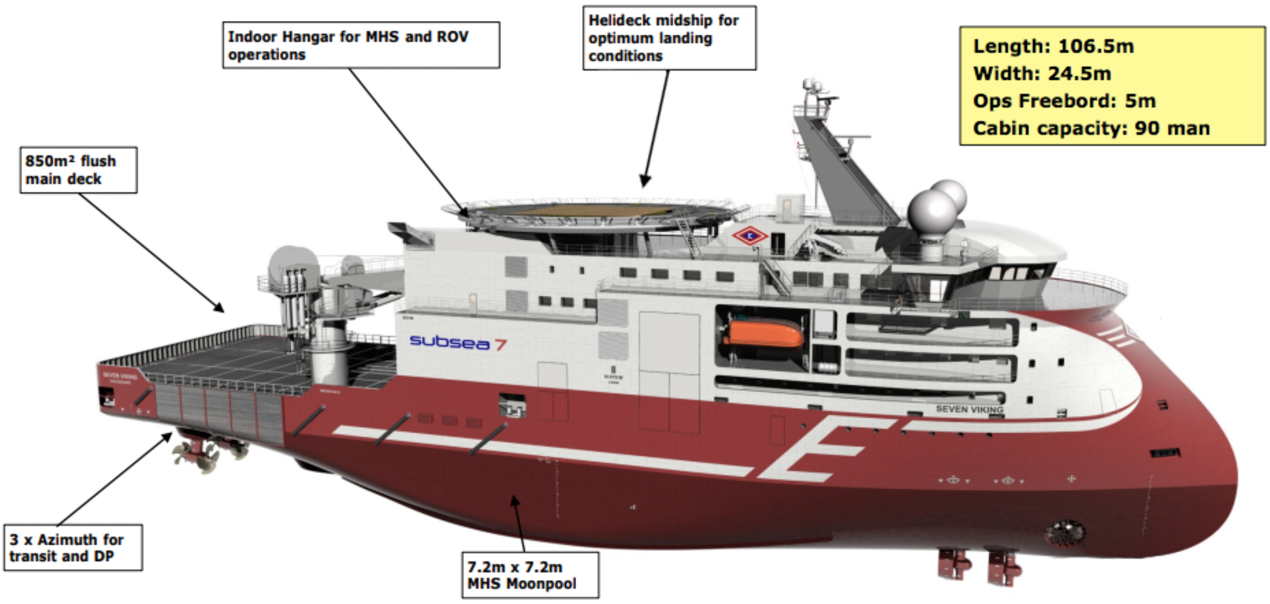


Figure 18 – "Seven Viking" vessel specification [16]

To have a complete picture of vessel classification and work they are performing figure 19 is provided below. It gives a general overview of respective subsea equipment and vessels, which are going to be discussed throughout the thesis.

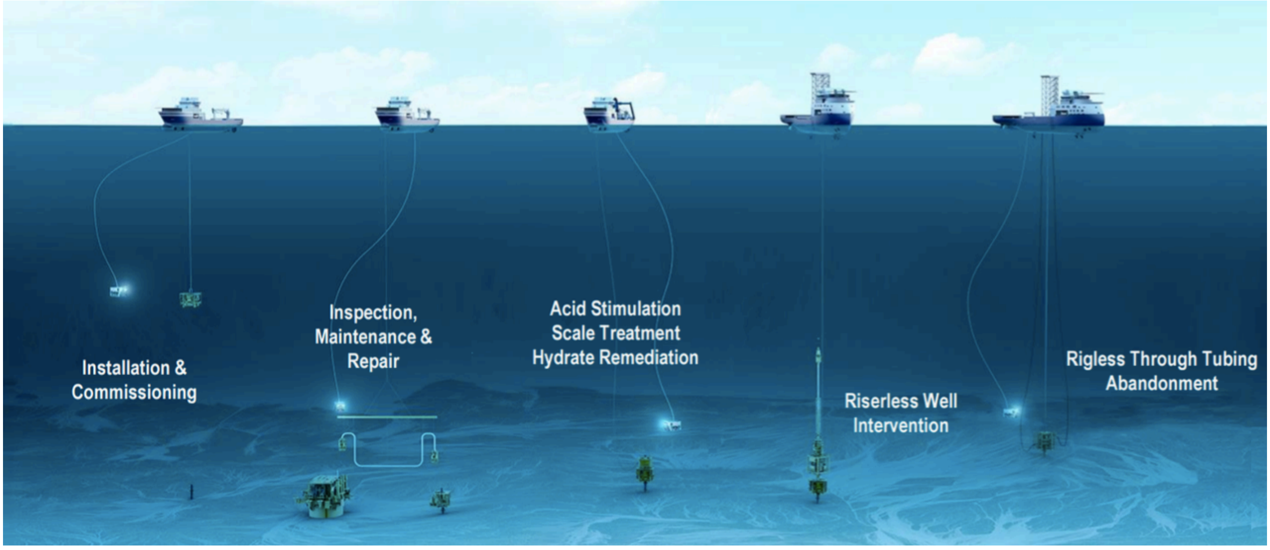


Figure 19 – Subsea well intervention classification [13]

3.4.2 NCS operating units overview

Mobile units that perform petroleum operations (drilling, well interventions, etc.) before operating are obligated to obtain the acknowledgement of compliance (AoC) and persuade Petroleum Safety Authority of Norway that petroleum operations can be pursued by a mobile facility in compliance with the regulations. Obtaining AoC is mandatory for [2]:

- Drilling units
- Accommodation units
- Floating production, storage and offloading units (FPSO)
- Well intervention units

The only exceptions include facilities, which are operated directly by the operator-company and regular storage ships. Such units instead of AoC need only a consent (allowance for the operator to execute the activity within regulatory parameters and in line with the details provided in the consent application). [2]

From September 2000 to November 2017, in total 63 units of 19 companies received acknowledgement of compliance from PSA. Almost 90% of these units are semi-submersible rigs and jack-up rigs, and only 5% stands for RLWI vessels (figure 20).

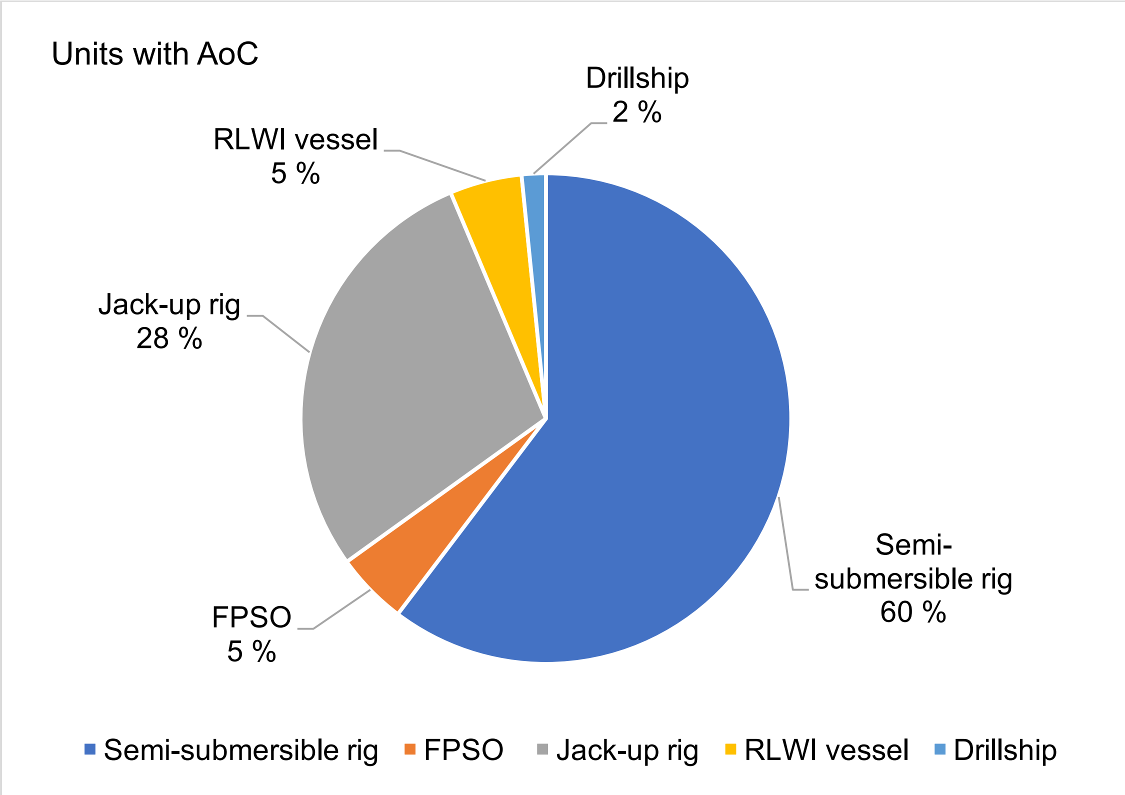


Figure 20 – NCS offshore unit distribution [2]

On figure 21 it is visible, that since year 2000, there was generally a positive trend and number of units were increasing, however during next 3-4 years most likely there will be a very small number of newly constructed units registered due to low oil price from 2014 to 2017 and, therefore, shortage of funds in the industry.

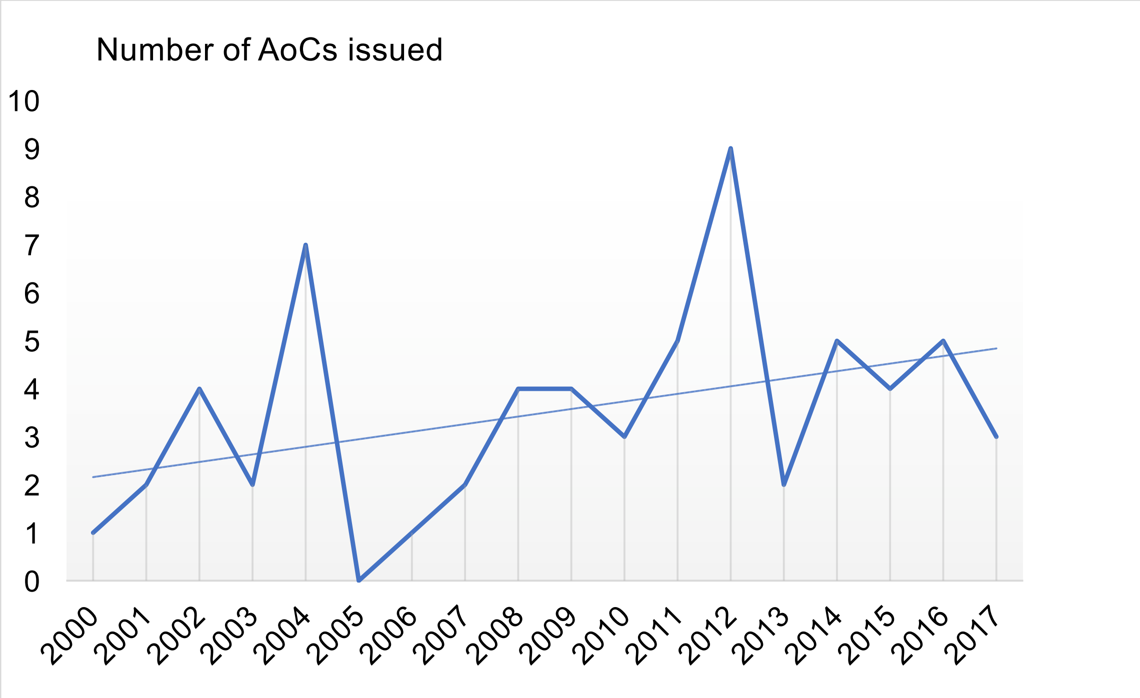


Figure 21 – Number of issued acknowledgements of compliance on the NCS by year

On the other hand, number of companies performing IMR activities on the NCS is high and the number of IMR vessels respectively. The first reason for this could be the fact that such companies work under marine regulations, which are quite similar in different countries, and do not require completely different permit compared to LWI operations. The second reason might be a higher demand for IMR operations compared to light well intervention activities. On the whole, fleet operating on the Norwegian continental shelf is new and modern according to the graph.

4 Inspection, maintenance and repair operations

Following chapter gives an overview of subsea maintenance operations which were performed on a Wintershall operated field (here and further field A) throughout the last eight years. Based on the analysis of these activities and the evaluation of related problems, recommendations for improvement and operational time benchmarks were created, which can be found in the last section of the chapter.

4.1 Field A subsea installations

For a better understanding of IMR activities at the field, a layout of the field with the location of templates is provided in figure 22. Templates are connected to each other with a production pipeline, umbilical and MEG line, and linked to the host platform, where the produced liquid is processed. Each template has four slots for the wells, and these wells are labeled with the numbers from 1 to 12 for simplification as it is shown in the figure below.

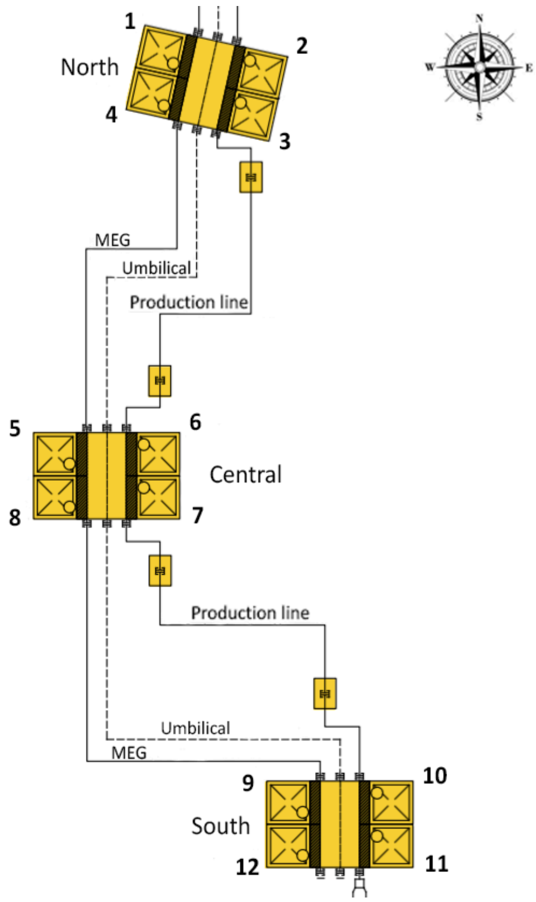


Figure 22 – Field A layout [23]

Listed in this chapter IMR activities are performed by interfering with subsea templates. Therefore, specifications and main elements of the typical field template are presented in figure 23. North, Central and South templates of the field A will be called Template N, C and S respectively further in the work.

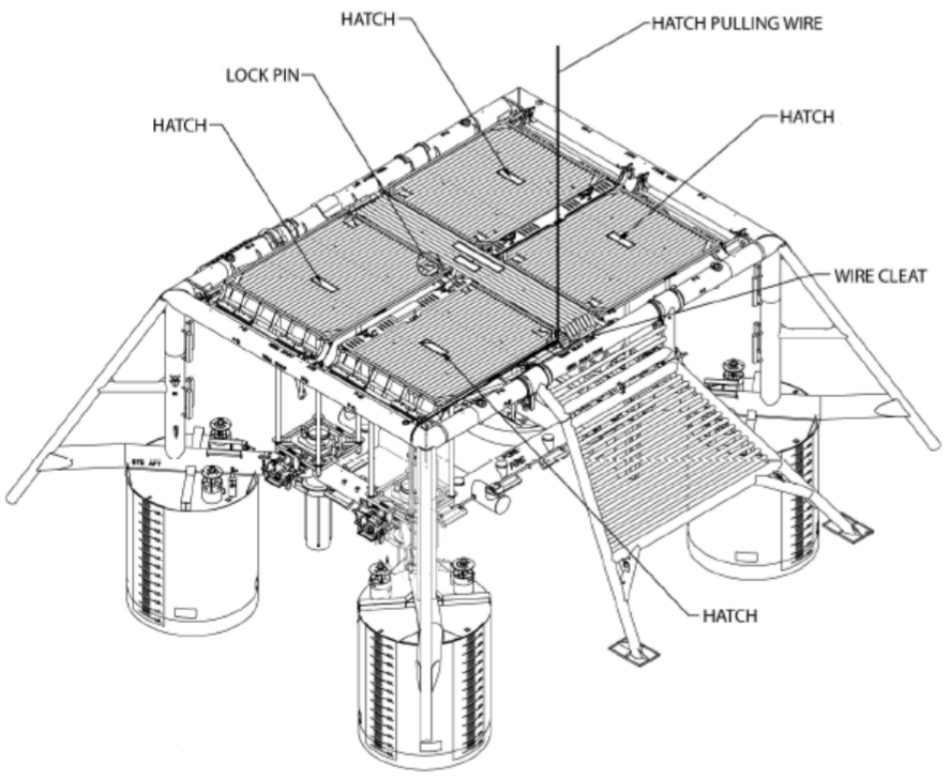


Figure 23 – Integrated template structure [20]

Figure 24 demonstrates running tools of the enhanced Xmas tree and attached to it control module and choke module. Such running tools are used to lower down to the seabed or lift the equipment onboard of a vessel. [24]

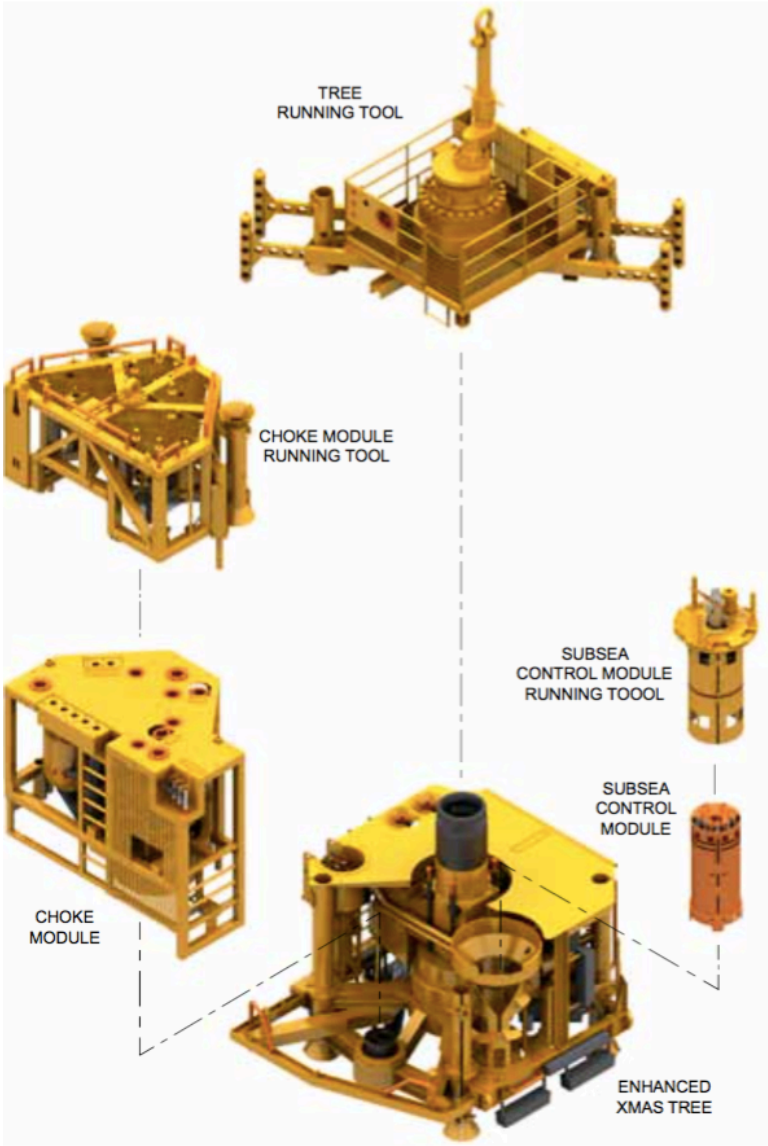


Figure 24 – Enhanced Xmas tree, choke module system overview [20]

4.2 Operation 1 – Pig launcher retrieval

4.2.1 Description and operation summary

The first operation, which is going to be mentioned in this chapter is pigging. Generally, pigging refers to the practice of using devices known as "pigs" to perform various maintenance operations, without stopping the flow of the product in a pipeline. Pigging operations are done for several reasons, which are [25]:

- Pipeline clean-up (clean solids, scale, paraffin and other debris from the pipe wall to keep pipeline flow efficiency on a high level)

- Batch transportation (separate the variety of hydrocarbons that are transported through the line)
- Prevention of solid accumulation and corrosion
- Inspection (the most common operation).

Pigging operations require a device to launch/retrieve a pig into/from a pipeline (figure 25). Hence, operation #1 implies retrieving of old pig launcher and installing a new one, following by pigging.

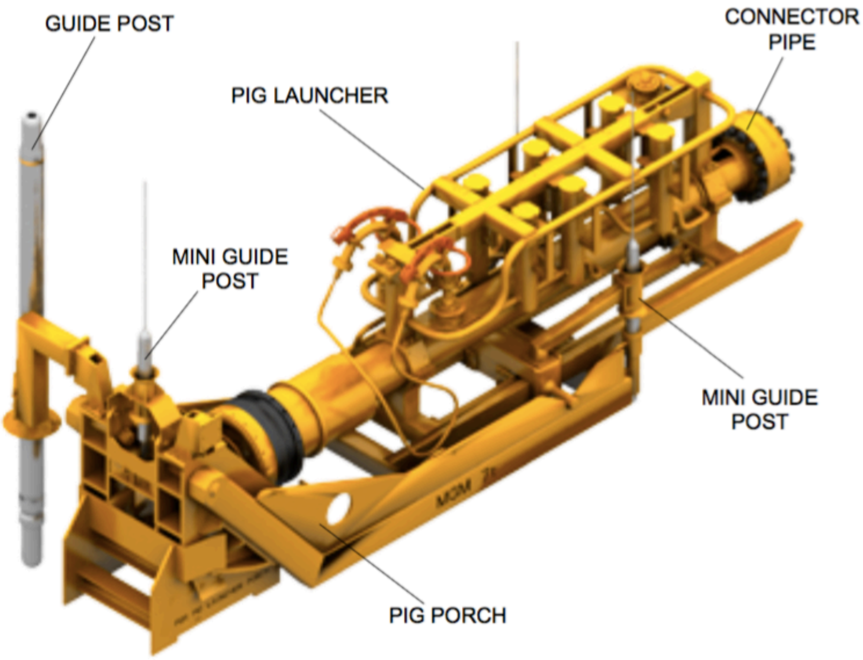


Figure 25 – Pig launcher and porch [20]

Table 5 indicates relevant information related to the pigging and corresponding operations.

Operation name:	Pig launcher retrieval
Type:	Repair
Scope of work:	Replace an old pig launcher; perform pigging and install high pressure (HP) cap with an intelligent pig.
Location:	Field A, Template S
Total work duration:	181,3 hours (7,6 days)

Downtime:	8,6 hours
Vessel used:	"Seven Viking" Subsea7

Table 5 – Operational summary 1

4.2.2 Results and observations

The pig launcher (PLR) was installed after the second attempt. The first attempt failed because while deploying the launcher on the seabed it became pressurized due to closed valves and there was no possibility to remove temporary protection cap and connect the PLR. Later, the PLR was recovered on the deck and following re-deployment was successful, besides the fact, that at the seabed some additional time was spent to clean the pig launcher by HP water jet.

During the pigging four cleaning pigs were used and all of them successfully arrived at the platform. However, sensors on two out of four retrieved pigs appeared to be turned off, and, therefore, no data was received from the data logger. The intelligent pig could not record data as well, because of a short-circuit caused by water ingress to one of the pig components.

While performing the last part of the work, leakage was detected within the area of HP cap connection. After solving the problem and proper cleaning of the connection, the new HP cap was finally installed. [24]

4.3 Operation 2 – Choke module replacement

4.3.1 Description and operation summary

Choke modules (CM) are essential parts of subsea production and corresponding operations such as water or gas injection, gas lift and reverse flow, they are fitted on a Xmas tree (figure 26), and can be retrieved and changed out when needed. Typically, choke modules have the functionality to [9]:

- Start-up and shut in subsea wells
- Balance pressure from different wells to a common manifold
- Reduce flowline pressures

- Protect against reservoir collapse
- Protect subsea gate valves from high-pressure drops during start-up and shut down.

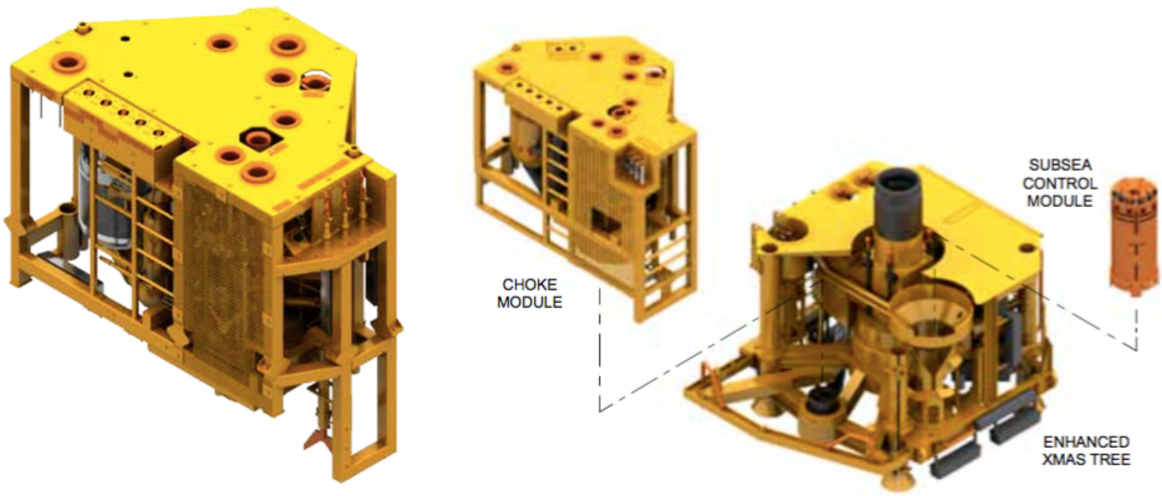


Figure 26 – Choke module system [20]

Due to constant wear of chokes, they require frequent maintenance activities and repair. Therefore, next operation is quite typical and very common IMR activity and is a subsea choke module replacement.

Operation:	Choke module replacement
Type:	Repair
Scope of work:	Replace the choke module
Location:	Field A, Template N, Well 1
Total work duration:	51,4 hours (2,1 days)
Downtime:	6,7 hours
Vessel used:	"Edda Fauna" DeepOcean

Table 6 – Operational summary 2

4.3.2 Results and observations

Valve operations were carried out according to the instructions and work program. Old choke module and following equipment (connectors and jumpers) were flushed before dismantling. After that, the jumpers were disconnected, and CM was unlocked and successfully brought to the deck. After additional cleaning of the manifold and Xmas tree, new choke module was installed. During the operation, there was a time delay due to a twist on the guidewires and additional cleaning procedure. Also, in the operation procedure plan, there were mentioned five jumpers on the SCM, while the actual number was 7, and this caused the delay needed to clarify everything. Another issue was an additional unplanned load on guidewire winch while opening hatches on the template. Even though it did not increase downtime and did not cause any failures, the procedure should be updated. [24]

4.4 Operation 3 – Sand detector replacement and leak detector installation

4.4.1 Description and operation summary

Operation #3 comprised sand detector (SD) replacement and installation of an acoustic leak and vibration detector (ALVD). The last type of detector can collect and transform signals into data sound that any leak causes, lying within a specific frequency range depending on the leaking fluid. The sound intensity of the leak is mostly dependent on the pressure difference over the leak orifice and the distance from the leakage point to the acoustic sensor. Those sensors are very common and have following benefits:

- Rapid leak detection at leak source
- Detection of liquid and gas leaks
- Relatively large subsea detection area (ca. 100m)

On the other hand, such detectors need to be very robust and, therefore, they tend to be quite expensive. Moreover, such tools should be regularly calibrated and inspected, to prevent false alarms, which can lead to production losses.

ALVD tool (figure 20) was installed on template S, and the sand detector was changed out on one of the wells. Summary of the operation and results are presented below.

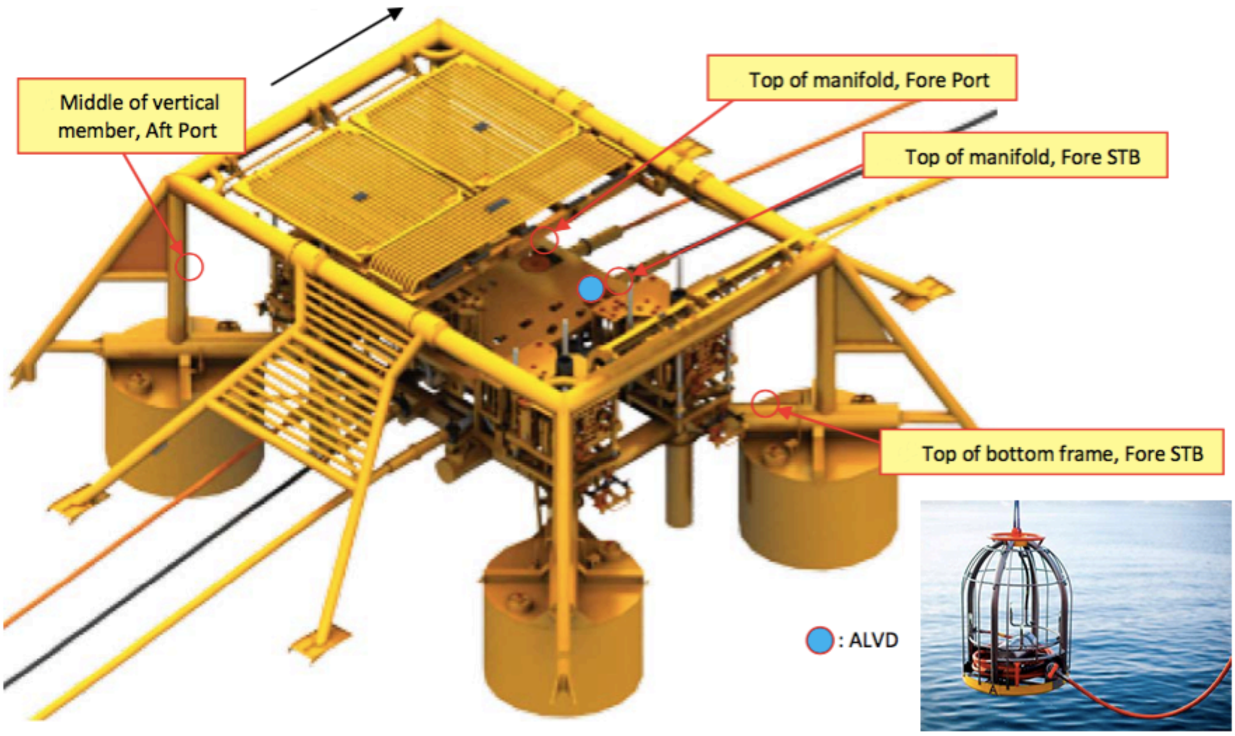


Figure 27 – ALVD tool location [20]

Operation:	SD replacement and ALVD installation
Type:	Repair + Maintenance
Scope of work:	To replace sand detector on a template and install acoustic leak and vibration detector
Location:	Field A, Template S, Well 10
Total work duration:	73,5 hours (3,1 days)
Downtime:	18 hours
Vessel used:	"Edda Fauna" DeepOcean

Table 7 – Operational summary 3

4.4.2 Results and observations

Firstly, ROV cleaned the future ALVD setting place on the manifold with the water jet. Then, the detector was deployed on guide wires through the moonpool and guided into place by ROV. After that, the ALVD was locked to the manifold and connected according to the procedure. Later, vessel crew started to work on the next operation, a sand detector replacement. During the operation, there were several problems (i.e. choke module running tool (CMRT) could not entirely land onto the CM in the first run), but finally, the choke module was retrieved by CMRT, the sand detector was changed and then CM was successfully landed back onto its place. Additionally, it was noticed that not all gas was flushed out of the CM prior to disconnection and lifting the module onto the vessel. [24]

4.5 Operation 4 – Scale treatment

4.5.1 Description and operation summary

Purpose of the next operation was to remove scale from the well. Scales can block the perforations, cover casing and production tubulars, valves, pumps, and downhole completion equipment. Unless the process of scale accumulation is stopped, it can subsequently reduce the production and even lead to the abandonment of the well. Therefore, scale treatment should be done from time to time, and the main remediation techniques are [26]:

- Milling (due to the brittle composition of scale it can be removed by deploying special bits inside the well via coiled tubing and following milling)
- Jetting (more effective on the soft scale)
- Chemical dissolution – scale squeeze (pumping acid inside the well to dissolve scale)

Out of three methods, scale squeeze is the most common on subsea wells. In addition, inhibitors can be used straight after remediation to prevent quick scale build-up.

Before the scale treatment activities, there was also conducted a fault finding on the well 12 on the field A. Short summary of the operation is presented in the table below.

Operation:	Scale treatment
Type:	Maintenance/repair

Scope of work:	Perform fault finding and following scale treatment
Location:	Field A, Template S, Well 12
Total work duration:	61,3 hours (2,6 days)
Downtime:	1 hour
Vessel used:	“Edda Fauna” DeepOcean

Table 8 – Operational summary 4

4.5.2 Results and observations

First step of the operation was to lower down the ROV and open the needed hatch. After the valve operations and cleaning, a successful leak test and pressure test was performed. Pumping operation itself took about 5 hours. By the end of the acid squeezing, the running tool with external tree cap (ETC) was recovered to the deck, temporary abandonment cap was installed on the re-entry hub and preservation liquid was pumped in. Last, the hatch was closed and the operation was completed. [24]

4.6 Operation 5 – Subsea control module replacement

4.6.1 Description and operation summary

Subsea control module (SCM) is an independently retrievable unit (figure 28), which is commonly used to provide well control functions during the production phase of subsea wells. Typical well control functions and monitoring provided by the SCM are as follows [27]:

- Actuation of fail-safe return production tree actuators and downhole safety valves;
- Actuation of flow control choke valves, manifold diverter valves and chemical injection valves;
- Monitoring of downhole pressure, temperature, and flow rate;
- Monitoring of production tree and manifold pressures, temperatures, and choke positions.

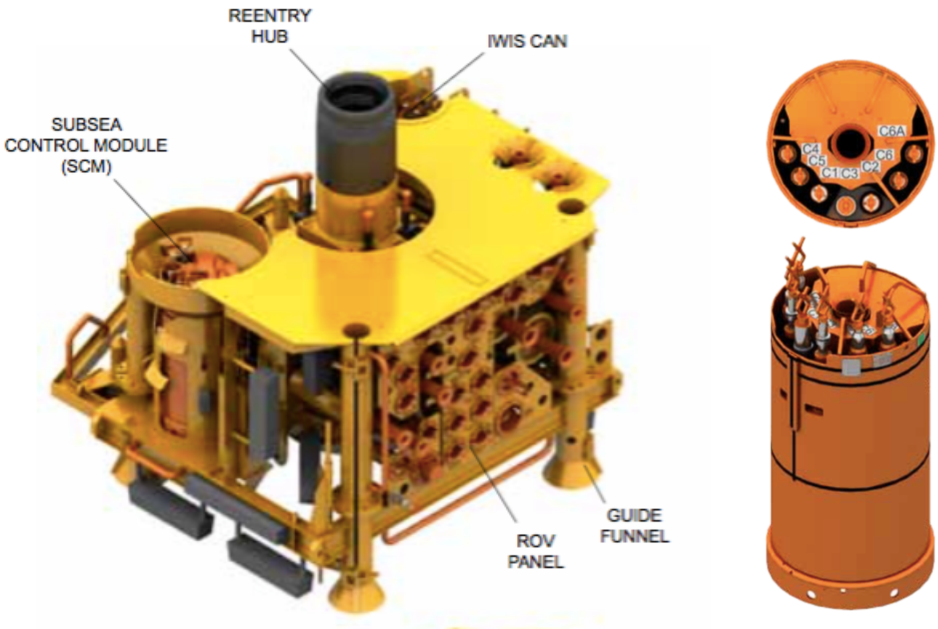


Figure 28 – Subsea control module system [20]

The SCM contains electronics, instrumentation, and hydraulics for safe and efficient operation of tree valves, chokes, and downhole valves and lands on Xmas tree as it is shown on figure 28. Purpose of the operation #6 is to replace such SCM module on one of the wells in the field A.

Operation:	SCM replacement
Type:	Repair
Scope of work:	Replace subsea control module and commission new SCM
Location:	Field A, Template S, Well 10
Total work duration:	20,1 hours (0,8 days)
Downtime:	N/A
Vessel used:	“Edda Fauna” DeepOcean

Table 9 – Operational summary 5

4.6.2 Results and observations

Decommissioning and retrieval of the old SCM started with preparatory work, which included as-found survey, hatch opening, verification of operating valves and disconnection of jumpers. After that, the old SCM was recovered to the deck and blanc space was cleaned. Then running tool successfully landed the SCM to the tree and it was connected to the jumpers. All interventions were executed according to the plan, fast and without any serious interruptions. [24]

4.7 Operation 6 – Annual inspection

4.7.1 Description and operation summary

Apart from maintenance and repair activities, inspection is another essential subsea activity type, that provides continuous production and mitigates chances of malfunctions occurrence. Inspections should be performed on a regular basis and give complete information about the subsea facilities. Remotely operated vehicles (ROVs) are typically used to inspect seabed structures. Wintershall performs ROV inspections on its fields annually, and here is the list of operations, which were performed on the field in question during one of those inspections [24]:

- Protection structure and foundation inspection
    - Check for damage
    - Check roof panel and hatch locks/hinges
    - Check for scour and corrosion;
    - Cathodic protection (CP) measurement on each structure
    - Check overall anode condition
- Manifold
    - Check for leaks and damage;
    - Check for corrosion;
    - Cathodic protection measurement on manifold
    - Check overall anode condition
- Tree and control module
    - Check for leaks and HC accumulation under the roof
    - Check for damage and corrosion;

    - CP measurement on a tree;
    - Check overall anode condition
- Flowlines and umbilical terminations
    - Check for leaks / damage to flowline and umbilical termination;
    - Check for corrosion;
    - Cathodic protection measurement

Operation name:	Annual ROV Inspection 2015
Type:	Inspection
Scope of work:	Perform annual inspection of subsea templates with ROV
Location:	Field A, Template N, C & S
Total work duration:	11,4 hours (0,5 days)
Downtime:	N/A
Vessel used:	"Seven Viking" Subsea7

Table 10 – Operational summary 6

4.7.2 Results and observations

The inspection was performed as planned and no serious issues were found. Some comments from the inspection are listed below [24]:

- Locking rings on wellheads are in the same position as previously inspected
- CP readings ranged in the acceptable interval, indicating adequate corrosion protection
- Covers on some of the components were partly detached, however, it was fixed and can not be considered as a serious problem
- No shallow or ground gas observed during the survey.

4.8 Statistical observation and benchmarking

4.8.1 Benchmarks for operations

More accurate look at the operational sequence of the most common IMR activities allowed to compare them in detail and gave an idea to create time benchmarks for these operations, which are:

- Choke module replacement (operation 1)
- Subsea control module replacement (operation 2)
- Annual inspection (operation 3)

There were four annual inspections analyzed, four CM replacement operations and one activity related to SCM replacement (Appendix B). All of them were performed on the field A on one of three identical templates. The time indicated in the table does not include downtime and is based on best performance time. For operations 1 and 2 there were three types of benchmarks:

- Marine work activities (all operations, which were performed directly on the seabed with WROVs)
- Topside activities (preparatory work, testing operations, etc.)
- Total time of the operation

Operation	Marine activities	Topsides activities	Total time
Choke module replacement	32 hours 29 minutes	1 hour 6 minutes	33 hours 35 minutes
Subsea control module replacement	13 hours 10 minutes	6 hours 55 minutes	20 hours 5 minutes

Table 11 – Operational benchmarks 1

For operation 3 there was calculated total time benchmark and average inspection time per template. Important to mention, that inspection program might differ from year to year, however, in this case, basic program without any additional operations is presented.

Operation	Average per template	Total time
Annual ROV inspection	Should be no more than **3 hours and 40 minutes** if the scope of work is regular as the one described in section 4.7	Should be no more than **11 hours** if the scope of work is regular as the one described in section 4.7

Table 12 – Operational benchmarks 2

These benchmarks could be also applied for fields with similar subsea facilities operated by Wintershall.

4.8.2 Statistical results

Previously mentioned operations, that took place on the field during time interval from 2011 to 2017, were grouped by different criteria and the graphs indicating the time spent on IMR activities, were generated. In this section downtime mentioned earlier stands for time spent on repairs of failures and delays due to operational issues, and does not include waiting on weather, which appears as a separate value.

First graph shows time distribution based on the type of activity, either inspection, maintenance or repair. It is visible that most time was spent on repair activities, and the main contributor was the operation related to pig launcher replacement.

Typical scale treatment operation implies maintenance and repair at the same time, however on this graph scale treatment procedures which took place in 2014 and 2015 are subjected to the group “maintenance” for convenience.

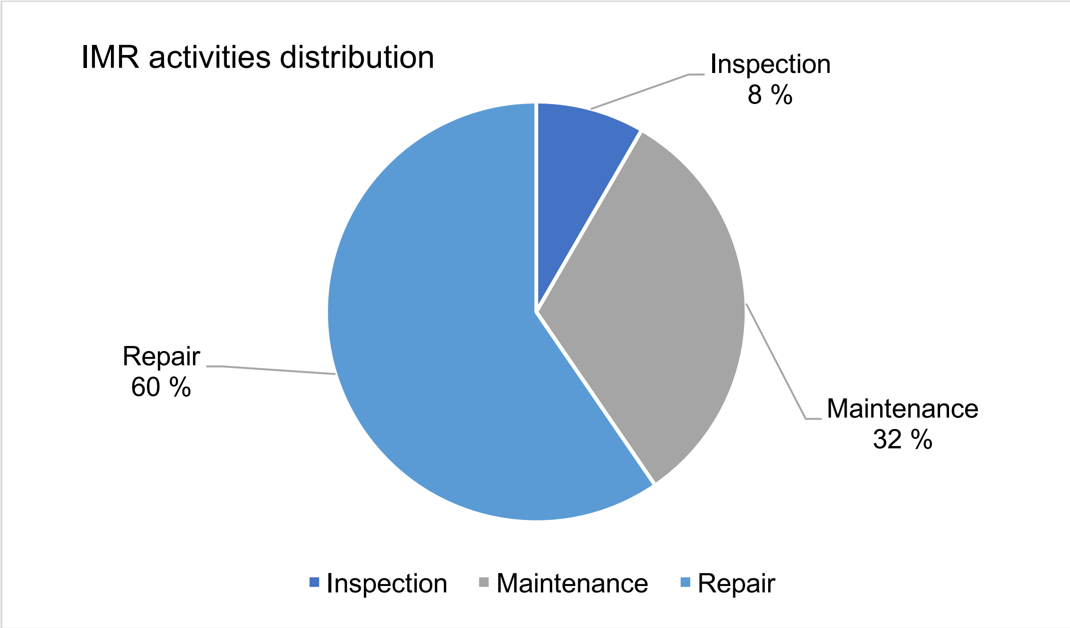


Figure 29 – Time distribution between inspection, maintenance and repair operations per period from 2011 to 2017

Second graph (figure 30) indicates how much time was spent on IMR activities for each year during the same period. Year 2015 was the most time-consuming year, due to several huge activities (PLR replacement and scale treatment procedure). Also, in this year, there was a transfer of the operational license for the field A from Equinor to Wintershall requiring additional subsea work for verifying integrity.

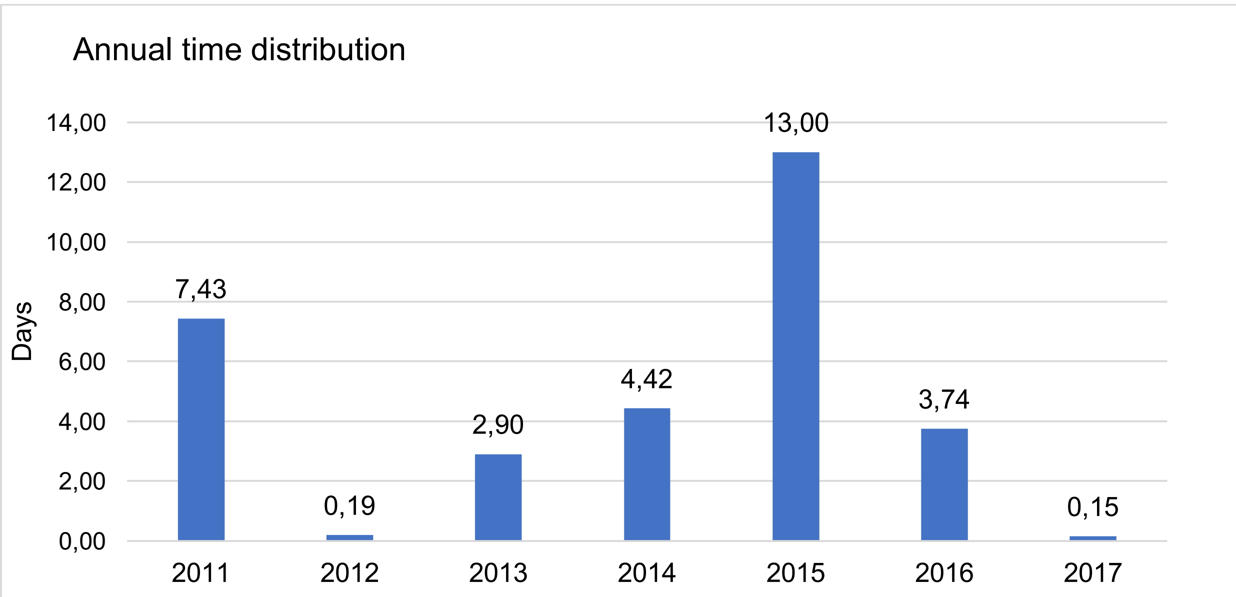


Figure 30 – Time spend on IMR activities each year from 2011 to 2017

Finally, figure 31 demonstrates time distribution based on the division into productive time (operational time), downtime and wait-on-weather (WOW) time. Downtime is a quite precise value and the estimation was performed based on the end of job reports.

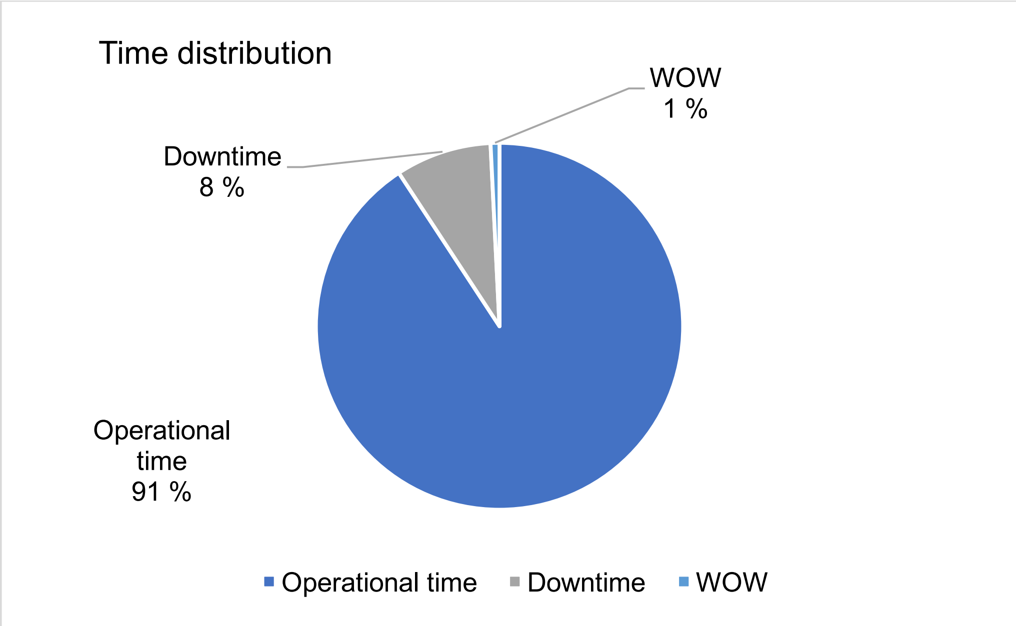


Figure 31 – Time distribution between operational time, downtime and waiting on weather for a period from 2011 to 2017

Data on the graph allows to conclude that time spent on waiting on weather conditions to improve is quite low. Out of 22 analyzed operations, there were noticed only two major cases of WOW. On the other hand, the value of the downtime is about 2,6 days, which is approximately 8% of the total time. Besides minor time consuming problems, such as delay in communication and additional water jetting, there were several bigger problems, which were:

- Failure to retrieve CM in the first run and following adjustments
- Failure to install an external tree cap during preparation for scale treatment, which led to delaying of the whole operation

Additionally, there were several instances when equipment was lifted back to the vessel due to not updated operational plans or other similar reasons. All of this leads to additional expenses and the main question is how to reduce time in general, and especially non-productive time. This is going to be addressed in the next sections.

4.9 Recommendations for improvement

The outcome of the typical improvements in our case would be increased efficiency, which means higher productivity of work and cost savings as a result. Strategy to achieve this outcome would be a review of current work processes and procedures. Recommendations for improvement are divided into four main groups by their relevance:

- Planning
- Organization
- Operational
- Safety

Each group is supported by specific examples from marine operations (from those mentioned above and from other case studies).

4.9.1 Improvement in planning

Planning implies performing research and establishing action steps for achieving goals. Within this group there were indicated the following recommendations for improvement:

- Work programs should be regularly updated
  - Hatch procedures should be updated on the field A to avoid snapping load when hatch turns over the balance point.
  - To avoid twist on the guide wires during marine operations vessel placement should be considered in advance, with respect to currents.
  - Method of gas evacuation from a choke module before lifting it onto the vessel should be evaluated to minimize the risk of gas release, which was observed during the sand detector replacement operation.
- Mobilisation task plans should contain all information regarding equipment and its placement
- Operational procedures should be re-checked if the same operation takes place in a different location
  - The same activity might require more time and this time could be wrongly considered as downtime.

- The period between annual inspections could be extended
    - If a subsea facility remains within a good condition and malfunctions are not observed, the margin of safety can be re-estimated, and next inspection might be scheduled to a later date.
- The previous performance of a service company on the same marine operation should be considered when evaluating a tender for the work
    - Time could be also reduced due to the learning effect of the vessel crew.
- Maintenance strategy can be adjusted based on the current economic situation in the industry
    - Preventive type of maintenance can be replaced by corrective (run equipment till it breaks down) when production is economically very beneficial and vice versa.

4.9.2 Improvement in organization

Organization process implies arranging tasks and resources and acts from transition planning to operation. For organizational optimization of marine activities following recommendations are proposed:

- Suppliers and service companies should have spare parts, which might suddenly be needed, due to incompatibility or damage of an initial detail (this relates to small and frequently used details)
    - During one of the choke replacement operations, there was lack of shear pins, so the sufficient number of shear pins with different tonnage should be added to the inventory.
    - While performing pig launcher replacement vessel crew required additional check valve to complete the operation, so searching of the detail led to delay in time.
- Valve status should be always obtained before the beginning of work
    - A problem of missing tags and incorrectly labeled valves on drawing of Xmas tree and manifold occurred during the barrier test on one of the operations.
- Time on waiting for permission receiving by mail during the operation should be reduced

    - Some permission request situations could be considered in advance, and action plan could be implemented.

4.9.3 Improvement in operations

When a plan for the activity was created, and everything is organized the operation can start. However, various setbacks occur throughout the process and here are several recommendations to minimize them:

- A short visual check of a facility should be done before starting an operation on the seabed
    - There was a delay in template hatch operations due to small problems with hinge locks.
- Constant ROV monitoring should be done, when certain operations are in progress
    - For instance, during pigging operations, radioactive isotope counters (RAIC) did not manage to count some of the pigs. Signal deflections were however indicated on RAICs when the pigs were passing. Hence, monitoring of pig counters with ROV is important and can help to detect a problem.
- Equipment spares should be reviewed carefully; in some cases, the necessity of having similar equipment sets could be absent.

4.9.4 Improvement in safety

Safety is an essential part of every marine operation, and HSE requirements should be always fulfilled and regularly updated. There are a number of risks related to marine operations and listed below recommendations for safety improvement which will help to mitigate those risks:

- Constant personnel training sessions and HSE courses should be conducted to create awareness of how to react in emergency situations and contingencies

- The risk assessment performed during the project stage should include all possible risks and ways of their mitigation. Also, the main outcomes of the assessment should be delivered to crew members and explained in a clear way
    - Particular attention should be paid to lifting operations due to severe consequences that might cause dropped objects on subsea facilities.
    - Any possible emissions during marine operations that can cause personal injury to employees or damage the environment should be identified and reduced to the minimum
- All vessel crew members and visitors should be provided with a vessel safety orientation after arrival on a vessel and prior to participation in any field activities.
- Audits, reviews and visual checks of tools, equipment onboard and materials should be done on a regular base to prevent injuries to the personnel
    - Unsafe conditions (i.e. defective tools) and personal factor (i.e. inattention) are two main causes of HSE issues appearing during marine operations according to data from Subsea7.
- After releasing a tender for subsea work, the company should carefully analyze HSE policy and history of accidents of candidates aiming to perform subsea service work.

5 Light well intervention activities

The objective of this chapter is to present one of the techniques of performing well interventions in the North Sea, by providing two examples of regular well interventions from the industry, and then assessing a possible improvement within LWI activities.

5.1 Well intervention sequence

The way of performing light interventions is similar within the whole Norwegian continental shelf and implies preparatory work, installation of pressure control equipment and the intervention itself. Light interventions can be performed by means of wireline and by utilizing coiled tubing.

When a vessel arrives on location, the first step is to connect a specific riserless light well intervention (RLWI) stack depicted on figure 32 to the Xmas tree. This stack allows controlling the valves on the subsea trees from a vessel. The stack has a lubricator system that enables wireline tool strings to be inserted into the wellbore under full pressure. Main components of the stack are depicted in figure 32, and are as following [24]:

- *Pressure control head* (PCH) creates a dynamic grease seal around the moving wireline and acts as a primary barrier towards the well
- *Upper lubricator package* (ULP) is the connection point for the PCH and has a wireline cutting valve, which acts as a secondary barrier element; includes the lubricator tubular.
- *Lower lubricator package* (LLP) – provides all electronic and hydraulic distribution to the subsea stack via umbilical
- *Well control package* (WCP) is the main barrier and has BOP function
- *Xmas tree adapter* helps to connect the stack to various types of subsea trees.

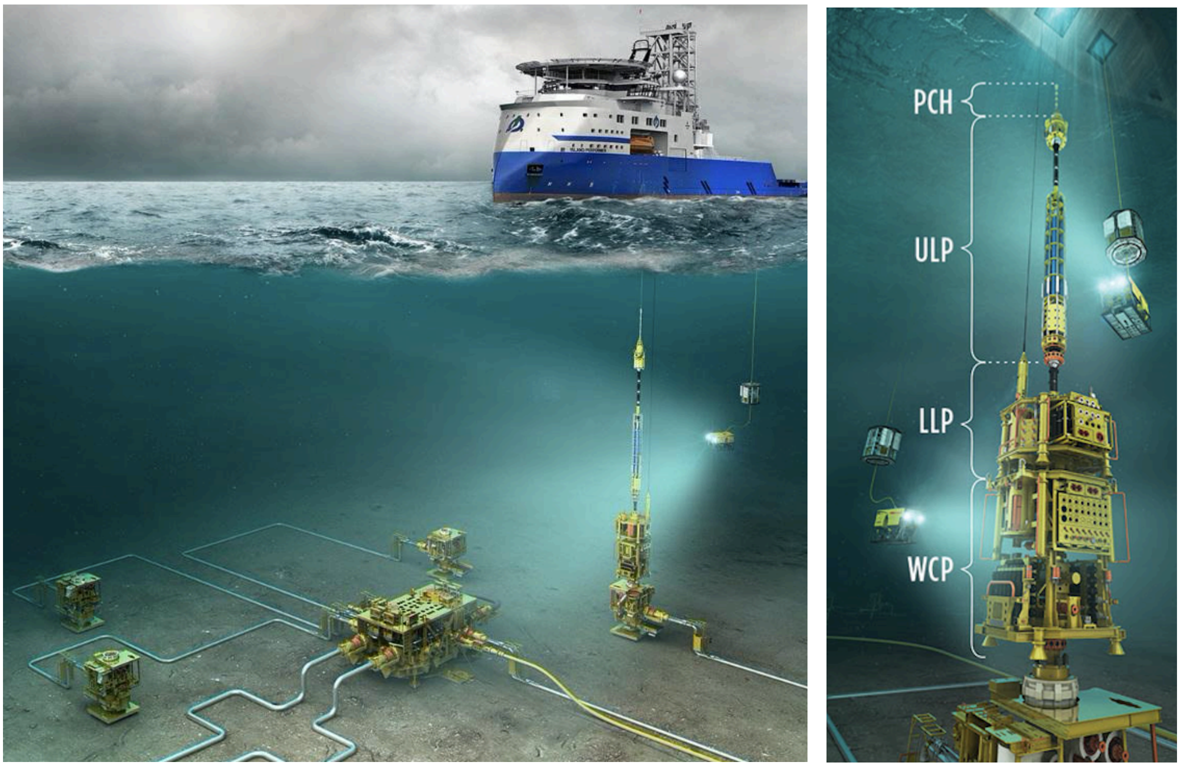


Figure 32 – RLWI stack structure [9]

Moreover, the stack is designed for well control operations of up to 6 500 ft (~1 981 m) water depth. It is also adaptable to all subsea trees — vertical and horizontal – and meets all NORSOK requirements, including subsea well control operations and wireline operations. [24]

5.2 Examples of LWI activities

Two examples of intervention activities with usage of previously described control package are addressed in this section. These activities also took place on the field A and were managed by Wintershall.

5.2.1 Operation 1 – Production logging test and optional zonal isolation

5.2.1.1 Theory and operation summary

Reservoirs in most cases produce water together with hydrocarbons, and when a certain level of depletion is reached within a producing layer, the well starts to produce more water than hydrocarbons. Therefore, layers are watered out and can cause lifting problems in the well and these layers need to be shut off or isolated. Before this, production logging test should be performed to distinguish clearly a non-productive zone.

Thus, the first example is devoted to diagnosing production issues. Initially, the problem was noticed by operational engineers and it indicated that water production is too high in one of the several zones of well 3 on the field A. Therefore, it was decided to perform production logging test and following plug installation. Some relevant information about this activity is presented in table 13. [24]

Operation name:	PLT and zonal isolation
Scope of work:	Perform production logging test and install a plug for isolating water producing zone.
Location:	Field A, Template N, Well 3
Total work duration:	172 hours (7,2 days)
Downtime:	19,3 hours (0,8 days)
WOW:	1,1 hours (0,1 days)
Vessel used:	“Island Frontier” Island Offshore

Table 13 – Operational summary 1

5.2.1.2 Results and observations

After arriving on place, it was performed a verification survey and following preparation operations (opening hatch, quick inspection, cleaning and connection of the stack). The whole operation was divided into 6 WL runs. Wireline runs #1 and #2 were performed to retrieve upper and lower crown plugs respectively (figure 20).

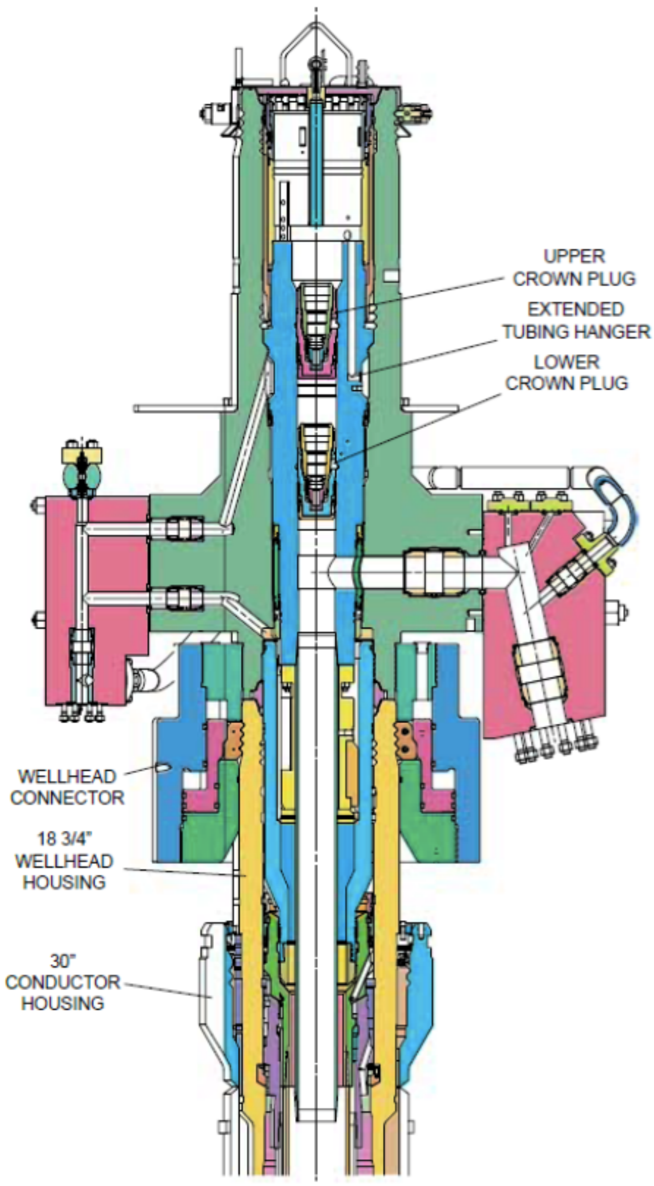


Figure 33 – Enhanced Xmas tree, cross section [20]

During the third run, a production logging string was run, which later showed that majority of the formation water is coming from Etive/Lower Ness, the lower reservoir section. The XY-caliper log showed no scale build up or ID reduction in the perforated section. Therefore, the company decided to proceed with an optional plug run for zonal isolation of Etive/Lower Ness. Next run was devoted to plug installation, which was situated below the Tarbert formation sand screen at the measured depth of 3 760 m, as it shown in figure 35.

During the last two runs (run #5 and #6) crown plugs were installed inside the Xmas tree and the operation was completed. However, throughout whole operation there were several problems with communication and alignment of horizontal Xmas tree adaptor, due to a manufacturing error. [24] Downtime (excluding WOW) was therefore quite high (figure 34). On the other hand, waiting on weather during the intervention was low and can be considered as acceptable.

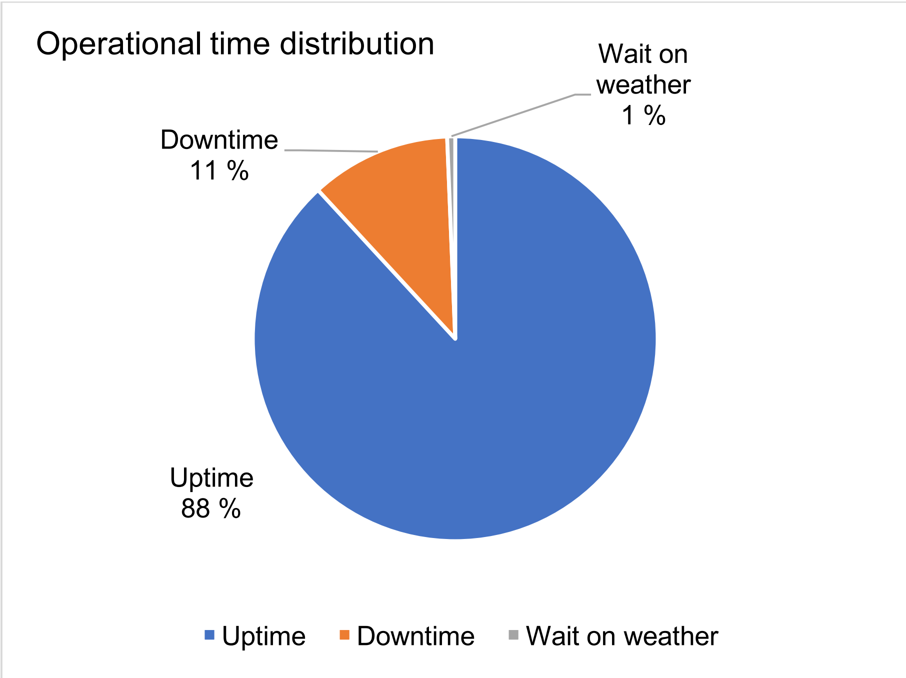


Figure 34 – First operation time distribution

5.2.2 Operation 2 – Injection valve replacement

The objective of the next operation was to restore the primary barrier envelope by replacing a leaking chemical injection valve (CIV) with a dummy valve. Location of the valve is presented in figure 35.

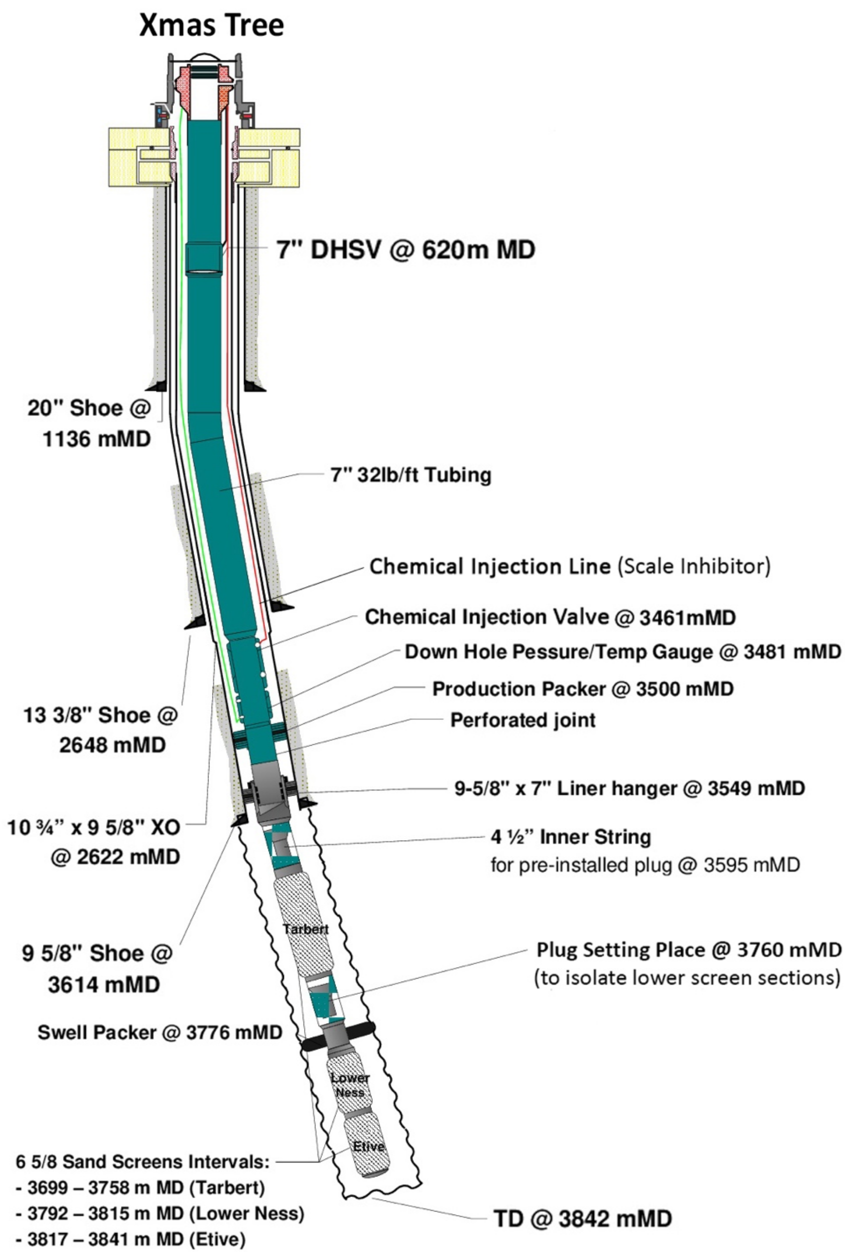


Figure 35 – CIV and zonal isolation plug location [24]

Preparatory work for the operation was quite equal to one described in the previous section and included: verification survey, hydrates removal from the hub and well control package installation. The intervention itself included six runs [24]:

- Retrieval of upper crown plug with a braided line
- Retrieval of lower crown plug with a braided line
- Chemical injection valve retrieval
- Installation of a dummy valve
- Lower crown plug installation

- Upper crown plug installation

Following pressure tests and decommissioning operations completed the work. A short summary of the operation is indicated in the table below.

Operation name:	CIV replacement
Scope of work:	Replace leaking CIV valve with a dummy valve
Location:	Field A, Template N, Well 3
Total work duration:	363,5 hours (15 days)
Downtime:	3 hours (0,1 days)
WOW:	244,8 hours (10,2 days)
Vessel used:	“Island Wellserver” Island Offshore

Table 14 – Operational summary 2

Due to the problems with ROV cage and ROV communication there was observed some downtime, however, the main contributor to non-productive time was waiting on weather (figure 36). Uptime in this case was only 32% of total work duration.

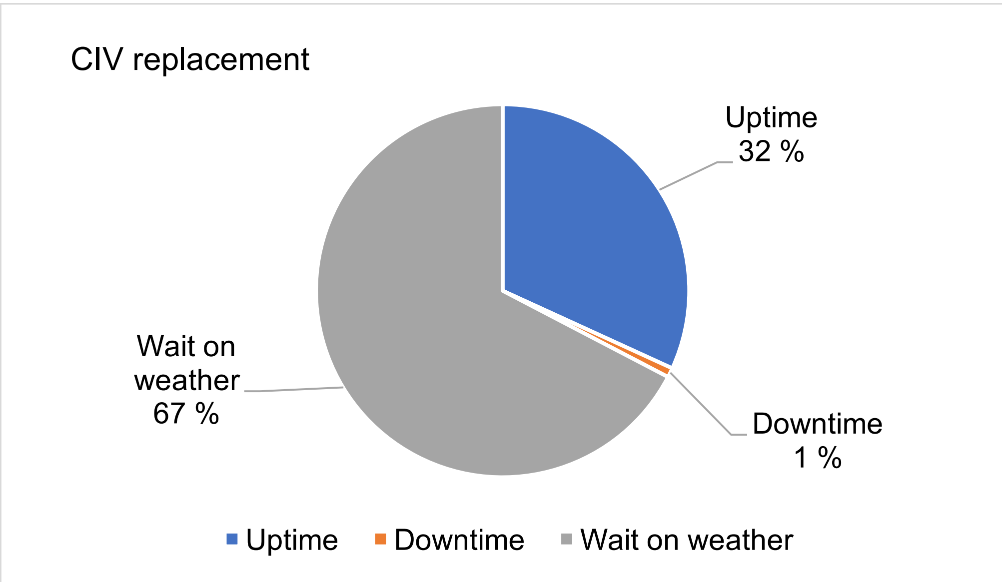


Figure 36 – Second operation time distribution

5.3 Recommendations for improvement

There were not as many LWI operations compared to IMR work performed directly by Wintershall. One reason is a frequency of such activities (LWI is performed less frequently than IMR), and another reason is that on some of the Wintershall operated fields well intervention work has been performed by Equinor. Nevertheless, out of the analyzed data and daily drilling reports several conclusions were made, which are:

- Wait on weather time was quite high during one of the operations
  - One solution is to manage to reserve a vessel for interventions during the planning stage for the summer period when the weather will less likely interrupt intervention activity.
  - Another solution is to shut in the target well and wait for better weather conditions before mobilization of a vessel (however, this idea works only if other wells from the field can be adjusted to higher rates to maintain the same level of production).
- A considerable part of uptime is being spent for ROV work instead of being reduced
  - ROV work should be optimized, and for instance, some operations can be done in parallel mobilizing two or three vehicles to minimize the flat time.
- Operational programs should be analyzed and updated
  - Some operations can be eliminated from the program due to their low necessity (i.e. guide wires are run every time, when a specific tool is deployed, however, in current practice there is no need to run GWs while running a wireline with a small detail, and when current is not that strong to displace a tool severely).
- Similar to the previous chapter, problems with communication were observed during the LWI activities
  - Improved communication with the well (data transmission) can be reached by planning and performing maintenance activities (i.e. annual ROV inspection) just before well intervention operations.
  - Communication with onshore office and tied production facility also take time, so, possible issues with equipment can be addressed in advance

(responsible person on the vessel should have the instruction of what to do in a particular situation).

- HSE training sessions and courses for personnel should be conducted on a regular base to create awareness of how to react in emergency situations and reduce the number of accidents and injuries
    - This and other improvements regarding health safety and the environment from section 4.9.4 can be applied to light well intervention activities as well because both (subsea IMR and LWI) are marine operations.

6 Plug and abandonment

This chapter aims to determine how certain plug and abandonment operations can be optimized by performing it from an LWI vessel instead of a rig, and how it will minimize downtime and costs of plug and abandonment in general. The section includes three subchapters, which indicate following information:

- Regulation requirements for permanent plug and abandonment
- Challenges related to P&A operations and a brief outlook on solutions
- Recommendations for improvement based on the stated techniques
- Discussions regarding proposed operational sequence changes

6.1 Requirements for P&A operations

Prior to listing the challenges and assess solutions it is important to mention briefly main requirements and Norwegian regulations for permanent abandonment activities.

First of all, permanently abandoned wells shall be plugged with an eternal perspective considering the effects of any foreseeable chemical and geological processes. [19] The result of permanent well plugging activities shall be individual well barriers or combined WBs, described in table 15.

Name	Function
Primary well barrier	To isolate a source of inflow, formation with normal pressure or over-pressured/ impermeable formation from surface/seabed.
Secondary well barrier	Back-up to the primary well barrier, against a source of inflow
Crossflow well barrier	To prevent flow between formations (where crossflow is not acceptable). May also function as a primary well barrier for the reservoir below.
Open hole to surface well barrier	To permanently isolate flow conduits from exposed formation(s) to surface after casing(s) are cut and retrieved and contain environmentally harmful fluids. The

	exposed formation can be over- pressured with no source of inflow. No hydrocarbons present.

Table 15 – Permanent abandonment barrier requirements [19]

Permanent well barriers shall extend across the full cross-section of the well, including all annuli and seal both vertically and horizontally. Generally, a permanent well barrier should have the following characteristics [19]:

- provide long-term integrity (eternal perspective);
- impermeable;
- non-shrinking;
- able to withstand mechanical loads/impact;
- resistant to chemicals/ substances (H_2S, CO_2 and hydrocarbons);
- ensure bonding to steel;
- not harmful to the steel tubulars integrity.

For P&A operations there are also additional WBE acceptance criteria, which are presented in table 16.

Element name	Additional features, requirements and guidelines
Casing	Steel tubulars WBE shall be supported by cement or alternative plugging materials.
Casing cement	Cement in the liner lap or in tubing annulus can be accepted as a permanent WBE when the liner is centralized in the overlap section. The casing cement in the liner lap shall be logged.
In-situ formation	The in-situ formation (e.g. shale, salt) shall be impermeable and have sufficient formation integrity.

Table 16 – Additional element acceptance criteria [19]

To ensure all requirements and set barriers companies typically retrieve production tubing from the wells, log old cement and install new plugs. The absence of ability to retrieve the tubing using a vessel requires the mobilization of a rig for the operation. Therefore, P&A cost dramatically increases causing huge expenses for the companies. This and other challenges are described in the next section.

6.2 Associated challenges

Subsea plug and abandonment has always been considered as a quite challenging activity. Therefore, a big range of difficulties related to the operation can be stated. Some challenges which mostly depend on properties of a field or a well and geology are as follows:

- high temperatures;
- unconsolidated formations;
- deep section milling and swarf transportation to the surface;
- changes in the formation strength because of depletion;
- unknown ultimate reservoir pressure after abandonment;
- formation permeability;
- sustained casing pressure;
- lack of data from old drilled wells.

Probably, the biggest problem of subsea plug and abandonment activity is an extremely high cost of operations and procedure as a whole. Graphs from economic studies of P&A show that cost goes down when a vessel is utilized (figure 37). Therefore, it can go even lower, if the whole operation is performed by a vessel.

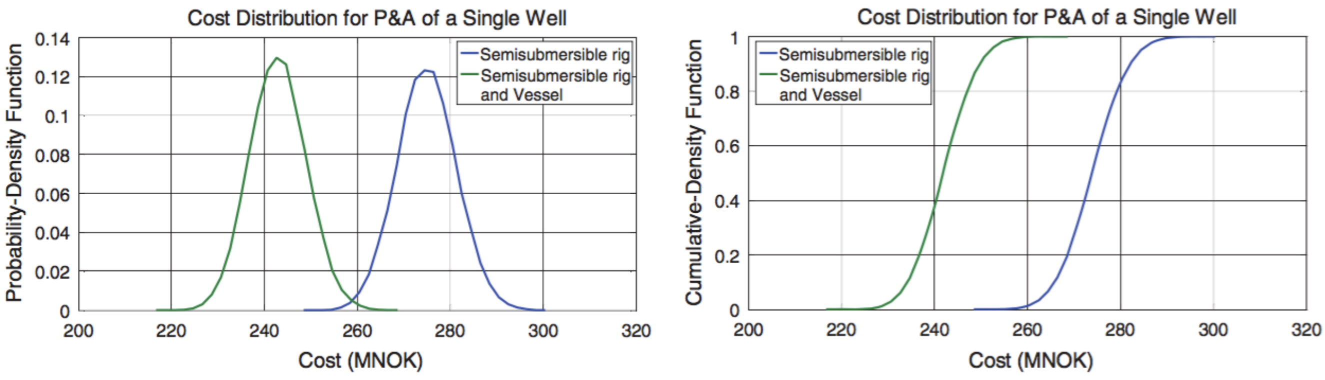


Figure 37 – P&A cost distribution [21]

Additionally, there was created a matrix, that provides information on the application of rigs and vessels for different operations and related challenges. The matrix was generated based on several reports and conference papers.

Operation/challenge	**Rig-based**	**Rig-less (vessel)**	**Comments**
Availability and mobility of units			Rig mobility is lower and this affects total expenses
Whole operational cost			Daily vessel rate is 30-40% lower comparing to a rig; total cost still need to be optimized
Killing the well/fluid circulation			Well can be killed through bullheading from a vessel, however, for traditional circulation procedures riser is required
Tubing/casing pulling			Not enough capacity on a vessel
Wellhead and conductor removal			Vessel can perform such operations on shallow depths; and for deep-water wells, it may be acceptable sometimes to leave or cover the wellhead/structure.
Milling operations			Generally expensive and time-consuming operation (alternative to tubing retrieval)
Control lines removal			Removed together with a whole tubing
Access to wellbore; phase 0			Vessel is more efficient in preparatory work
Isolating multiple reservoirs			Solution is to retrieve tubing or perform several milling operations
Capacity of the unit			Some vessels do not have enough deck space to fit new equipment

Color code	Can be easily done	Might be performed, but with some issues	Some difficulties with performance	Can not be performed or lots of difficulties

Table 17 – Operations matrix

Based on the matrix, a conclusion can be that the biggest problem about rig-less operations is the lack of ability to retrieve tubing. The solution could be to leave tubing in place providing an equally perfect seal as if the tubing had not been removed or retrieve it partly with vessel equipment. Additionally, leaving tubing in place eliminates the problem of utilization of old and damaged tubing. Several innovative P&A techniques solving this problem and other issues regarding involving vessels in P&A operations already exist, and they will be briefly discussed in section 6.3.

6.3 Solutions outlook

6.3.1 Enhanced well design

The first contributor to successful well abandonment is initial well design. Lack of P&A planning during the well construction phase can significantly add operational time and expenses.

To minimize possible negative consequences, these critical considerations (which should be addressed during the design stage) were identified:

- collect and keep as much information about the well and formation as possible throughout the well life cycle (this may include end-of-well reports, daily drilling reports, completion reports, logs, well integrity status, production history)
- verify the quality of cement by logging, when there is a chance to do it (this implies not only verification during the construction stage, but also production logging); [28]
- installation of control lines on the shallower depths and outside the tubing to create space for future barrier plug (approach was successfully applied on some wells, however, due to the placement of the lines in the upper section of the well, their efficiency decreases, and functions are limited);
- companies should be obligated to monitor B-annulus pressure and temperature constantly. [29]

These considerations may result in reduced cost, and, also, they create an additional positive background for the transition to rig-less P&A.

6.3.2 Formation as a barrier

Another concept that should be mentioned is considering formation as a possible barrier. More precisely, formations with very low permeability (shale or salt) may be considered as a natural annular barrier or in some cases even a full wellbore barrier. Using formation-as-barrier (FAB) concept would save costs on remediating the cement integrity behind the casing and provide the safest plugging material, by restoring the original seal.

There were several observations in the North Sea to identify the capability of FAB concept. The results (based on cement bond logs and pressure tests) indicated that in most cases creeping shales after decades demonstrated the same sealing effect as specifically performed cement job and entire Norwegian continental shelf zone (excluding the Barents Sea) could be considered as FAB area (figure 38). [30]

Figure 38 – FAB area on the NCS [30]

The closure rate of the gap between formation and casing can be affected by the following factors [31]:

- formation temperature (it will take the formation more time to creep, if the temperature is lower)

- composition (i.e. formation was damaged during drilling operations, therefore, it would not constitute a good wellbore seal; also, some rocks are reluctant to form a barrier)
- stress (overburden stress is the main driver, therefore, in deeper sections formation will most likely form a barrier faster)
- wellbore fluid density and temperature

Research identifying this concept and ways of monitoring sealing process is ongoing, thus, in the near future we can expect a better understanding of the mechanisms for shale barrier formation. The attractiveness of the method is an opportunity to restore self-healing and robust seal in natural and cost-effective manner.

6.4.3 Alternative plugging materials

Among traditional plugging materials and methods such as different types of cement and mechanical plugs, there is a wide range of alternatives applicable for different abandonment cases and purposes [32]:

- ceramics
- grouts
- thermosetting materials
- resins and gels
- metals (bismuth based)
- glass.

6.4.3.1 Bismuth plug

Bismuth in the role of a plugging material can solve a problem of damaged or badly corroded tubing and thus eliminates the necessity to pull out the tubing from a wellbore. The method implies creating a plug (figure 39) made of bismuth or its alloy, a metal with some great properties, which are [33]:

- low melting point compared to other metals (around 273°C for pure bismuth, or up to 50°C for alloy);
- viscosity similar to water when liquefied;
- high density (around 10 sg);

- expands upon solidification and cooling down (approximately by 3%);
- exceptional resistivity to corrosion (not affected by H2S or CO2);
- complete non-toxicity.

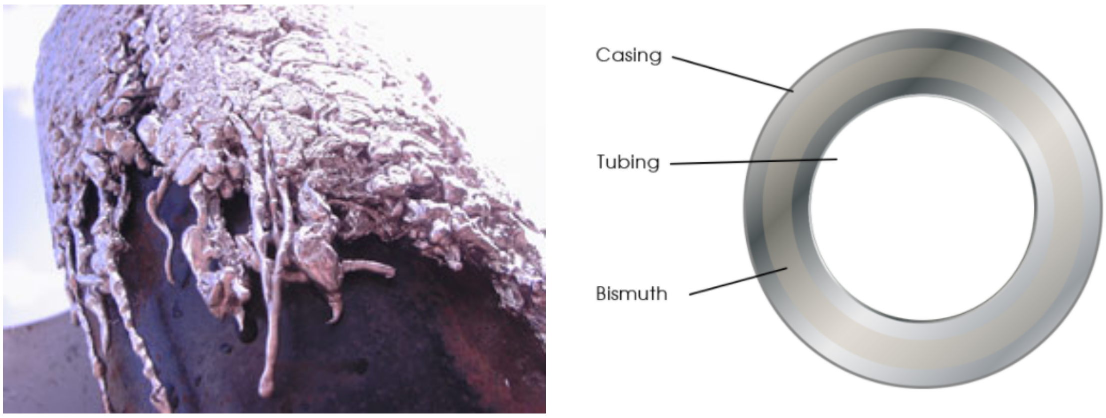


Figure 39 – Bismuth to casing connection [33]

Sealing approach is quite simple and consists of following steps [34]:

- deploy the tool with bismuth alloy and some thermite for melting
- ignite thermite and activate the melting process (melting temperature of bismuth is low, so, it will not damage surroundings);
- squeeze the substance through perforations, or into leaking areas of the casing to repair damages;
- wait on cooling down and solidification;
- needed plug is formed.

Even though it demonstrates excellent plugging properties, bismuth has, on the other hand, some drawbacks, which are as follows:

- not very stable at high temperatures and might creep, when in tension
- low expansion factor if bismuth is alloyed by other elements (might even drop almost to 0%)
- poor metal to formation bonding.

6.3.4 Interwell thermite seal

New and unique solution was recently introduced by the Norwegian company Interwell. The idea behind the concept is to restore original integrity of the formation by melting certain interval of the well and creating bonds using thermite and its exceptional properties. Such bonds will satisfy the requirements for permanent abandonment and contribute to P&A cost reduction. Table 18 presents essential information regarding composition, properties and application of thermite.

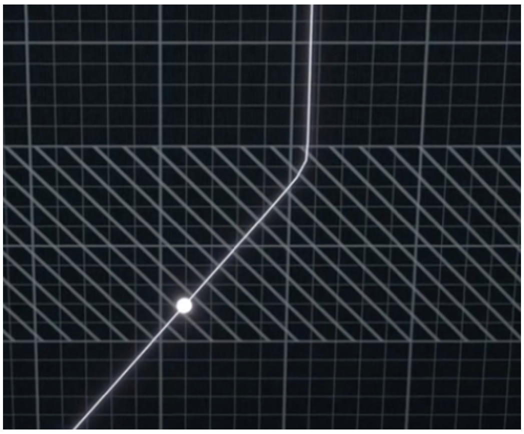
Description	A thermite reaction is one in which aluminium metal is oxidized by the oxide of another metal. Therefore, name thermite is also used to refer to a mixture of these chemicals.
Composition	Aluminium metal (other fuels could be magnesium, titanium, zinc etc.) and iron oxide (sometimes bismuth, boron, silicon and other oxides are also used).
Properties	• Usually deployed in form of powder • Burns at around 2 500 ℃ • Can melt through steel (tubing, casing) and able to melt surrounding rock • Bonds materials together after solidification
Reaction	When ignited by heat, thermite undergoes an exothermic reduction-oxidation reaction (examples of another oxidation reactions are rust creation and regular combustion)
Application	Commonly used in the welding process

Table 18 – Thermite properties and composition [35]

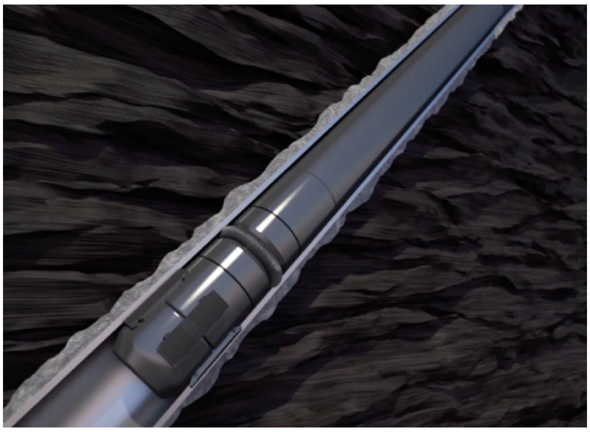
Sealing process is quite simple and consists of following steps [36]:

- Identifying perfect place to install thermite plug (figure a) based on geological data and wellbore equipment allocation;
- Deployment of first equipment set (which includes a mechanical plug or an anchor) by electric line (figure b) or coiled tubing (depending on amount of utilized thermite);
- Special heat-resistant material is released and evenly distributed above the plug to prevent it from burning (figure c);
- Lowering and positioning of the reaction triggering tool;
- Activating tool by electric signal, initiating a slow-burning exothermic reaction at extreme temperatures, that utilizes a great amount of heat in the wellbore and igniting melting process (figure d and e);

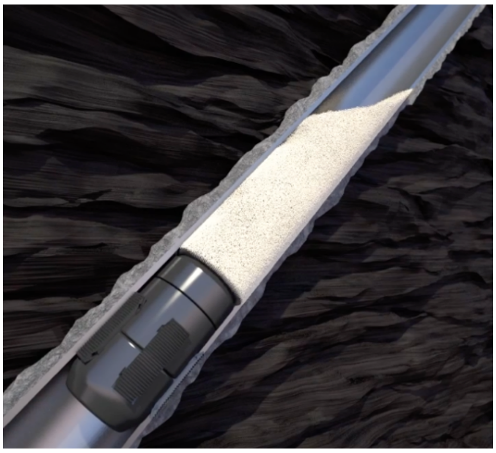
- The reactant melts through the wellbore and surrounding materials (tubing, casing, cement and rock), and bonds with the cap rock formation (figure e); reaction continues until no oxygen is left in chemical composition;
- Waiting on cooling and solidification;
- The result is a solid and impermeable barrier that extends across the full cross-section of the well and seals in both directions, vertical and horizontal, as it is required in the regulations (figure f).



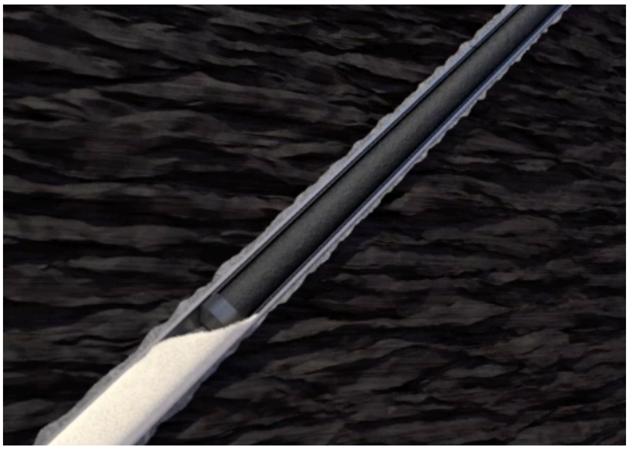
a) Plugging zone identification;



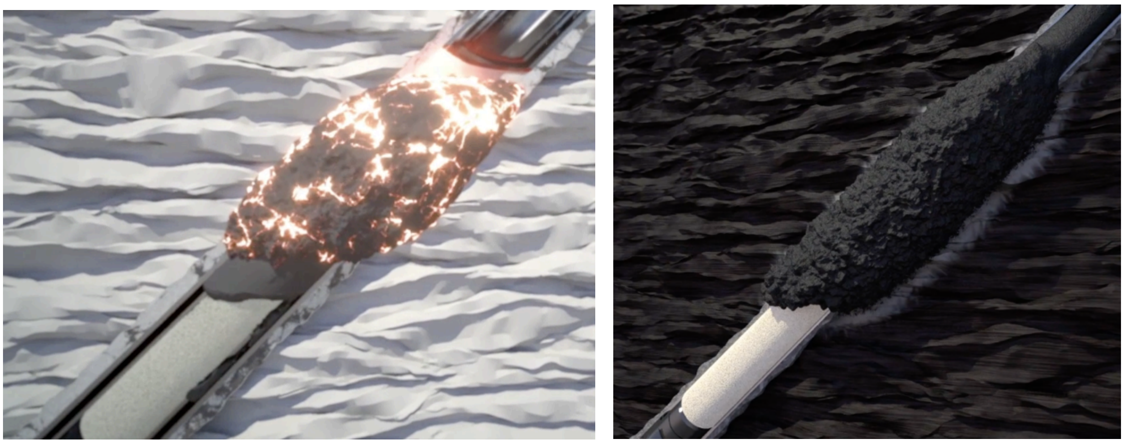
b) Isolating packer installation



c) Heat resistant assembly;



d) Thermite containing tool deployment



e) Exothermic reaction; f) Formed barrier

Figure 40 – Interwell thermite plugging procedures [36]

In 2017, two onshore pilot wells were successfully plugged and abandoned, and subsequently tested. [36] However, as every new technique, Interwell P&A technology has number of drawbacks and concerns, which are:

- lack of track record, due to very small number of tested wells
- obstacles related to regulations
- bonding of artificial rock to the formation
- chance of unevenly distributed flaring process, which can result in the creation of weaker areas, which will not ensure 100% sealing
- wireline deployment is under certain concern because the amount of thermite needed to create for instance 50 metres plug is huge; therefore, coiled tubing might be required.

The technique is new and requires additional scientific research and sustainability proof. What is more, there are several important factors, which can limit the well, that could be considered as a candidate for thermite abandonment, and these factors are [37]:

- Depth (recent test showed full integrity on 2 100 m deep wells, but possible problems related to deeper wells are not evaluated yet);
- Formation (some rocks would easily form an artificial plug, however, there are also unstable and not homogeneous formations, which might not establish perfect bonding);

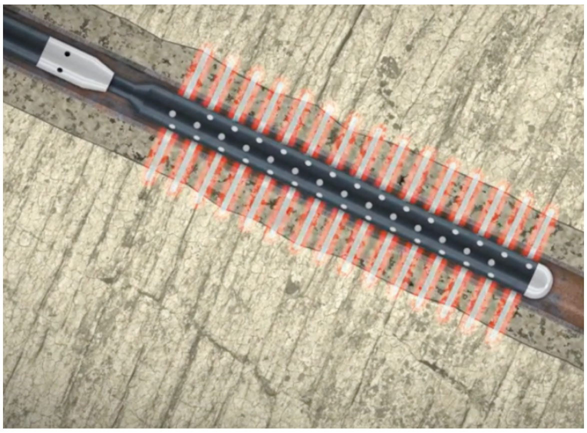
- Limited tubing/casing diameter (deployment tool can be positioned in a minimum casing diameter of 5 1/2”)

Revolutionary P&A technique utilizing thermite allows to leave all equipment in the well, which makes it ideal for rig-less application, but under certain considerations.

6.3.5 HydraWell perforate, wash and cement

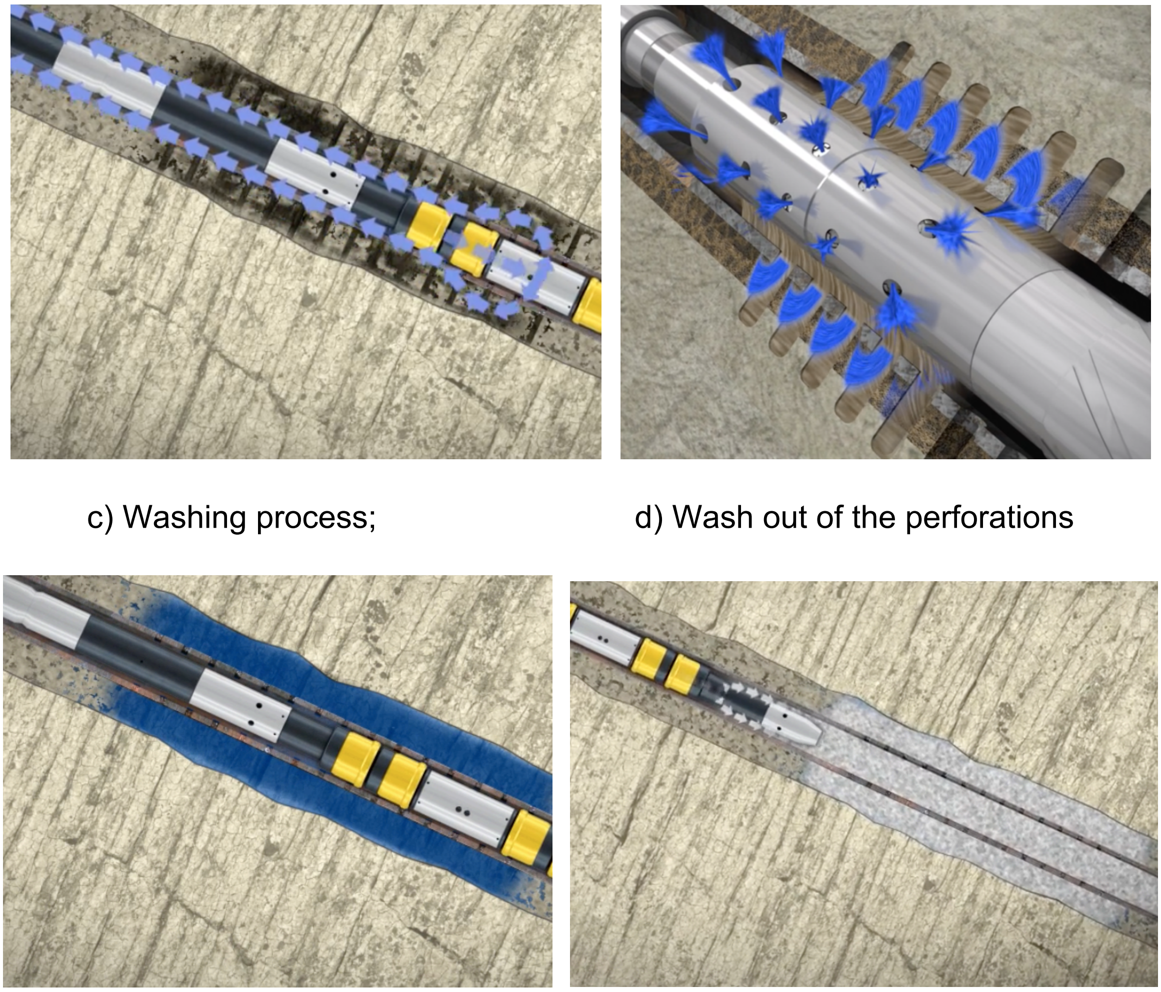
Another alternative to plug the well is to squeeze cement into perforated and cleaned holes. Technology is known as perforate, wash and cement (PWC). This approach implies four major steps, which are [38]:

- *Perforation stage* (perforation gun is deployed inside the well, and perforations are made within needed length and frequency as it is showed on figures a-b)
- *Washing stage* (when the gun is dropped, next tool washes out debris, old mud and cuttings to create a good environment for cement, which can be observed on figures c-d; special allocation of nozzles allows even water distribution throughout the P&A zone)
- *Cementing stage* (water is displaced by spacer, which is subsequently replaced by cement as it is presented on figures e-f)
- *Verifying plug* (pressure test or tagging; in some cases, tubing area should be drilled again to verify the quality of annuli cement plug)



a) Perforating stage;

b) Perforated plugging zone



c) Washing process; d) Wash out of the perforations

e) Washed zone; f) Cementing process

Figure 41 – HydraWell and Archer plug installation sequence [38] [39]

The technology is not limited to setting a plug through one casing. Few years ago, there was introduced HydraHemera tool by HydraWell, which washes through multiple perforated casings and allows to install high-grade cement plug behind tubing and casing. This approach significantly reduces the total time required for P&A compared to the conventional method (section milling). However, perf-wash-cement technology requires from a vessel full circulation ability right now. Additionally, there are several considerations and limitations regarding the technique, which are [40]:

- Barrier verification (in the current practice cemented area should be re-drilled and new cement behind casing should be logged)
- Rotation capability (to ensure perfect cement quality cementing tool needs to be rotated, as a vessel can hardly provide it, HydraWell works on creating a downhole motor specifically for its tools)

- Pumping/circulation capability of coiled tubing (CT should be able to ensure certain flowrate for good washing operations while cleaning the wellbore)
- Mud circulation system (as it was mentioned before, riser can ensure needed circulation rate, however, in prospect circulation system should be developed in a completely new way to allow riserless circulation)
- Risk of complicating the whole procedure (there is a certain risk related to the operation because if the cement will not pass verification then it should be removed by milling and this could take even more time and resources compared to traditional tubing retrieval)

There is also another HydraWell tool worth mentioning. HydraKratos is developed to induce a charge which can expand casing to the formation (figure 42) to establish a mechanical barrier and serve as a foundation for upcoming cement plug not allowing it to slump downhole as it is shown in figure 42.

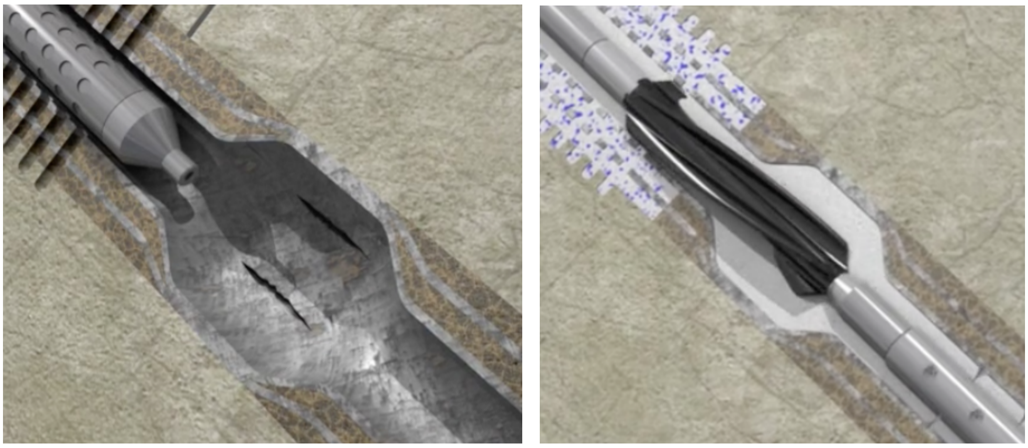


Figure 42 – HydraKratos tool effect and cement foundation [38]

6.3.6 Claxton well abandonment

Suspended well abandonment tool (SWAT) introduced by Claxton and their partners allows to set environmental and intermediate barriers on certain categories of the wells. Maximum setting depth of the barrier is about 731 meters below the mudline. [41] The configuration and elements of the tool can be observed on picture 43.

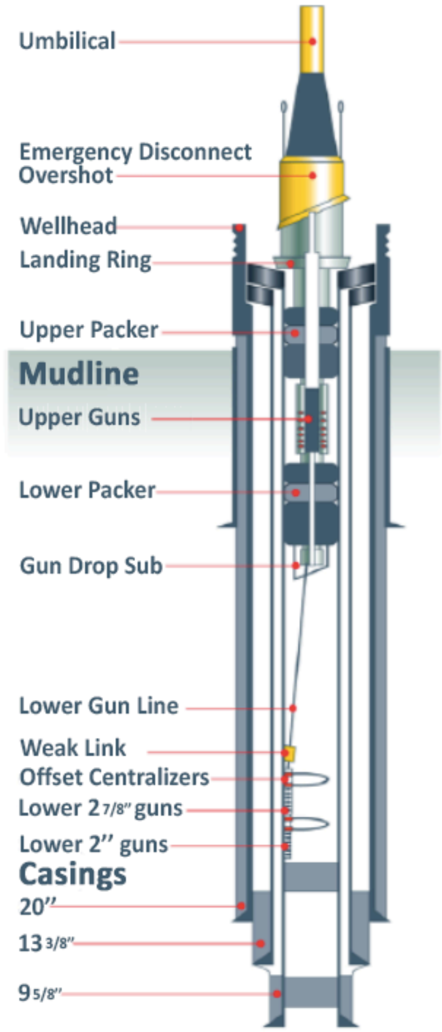


Figure 43 – SWAT tool scheme [42]

Plug setting technique includes following operations [42]:

- Positioning of the SWAT on the wellhead
- Performing casing perforations
- Recovery of the drilling mud
- Placing of the cement barriers

Even though the technology allows to set cement plugs without utilizing a riser and a rig, there is a number of disadvantages of the SWAT; together with the advantages they are stated in table 19.

Advantages	Disadvantages
Deployed from a vessel (LWI vessel or anchor-handling tug supply vessel)	Reservoir barrier should be already in place

No riser required	Production tubing should be retrieved
Perforation, circulation and cementation of multiple casings	Plug verification through multiple casings
Pressure test and cementing in one run	Water depth limitations
Successful track record	

Table 19 – Pros and cons of SWAT technology [42]

6.4 Example evaluation

There is no internal case history regarding P&A operations in the company, as it was for IMR activities and well interventions. Therefore, it was decided to take a P&A operational sequence and an average duration of each operation from the research paper. [43] Plug and abandonment work on a regular vertical well without any specific problems will be presented in this case. Operational sequence is divided into four phases and grouped in table 20. Each phase includes a list of activities and comments with alternative solutions.

An improved operational sequence can be reached by implementing some of the solutions mentioned before and trying to involve a light well intervention vessel (LWIV) into first and second phase. Such improved sequence might be considered in the future as a possible P&A plan for some Wintershall operating wells.

Seq. #	Operational description	Average duration	Utilized unit	Alternative/Comments
Phase 0 – Preparatory work				
1	Open hatch and pull tree cap	15	LWIV	
2	Run LWI stack and connect to vertical Xmas tree. Install kill hose.	36	LWIV	Regular marine hose can be used as well (the same as for the scale treatment procedures)
3	Perform caliper run	24	LWIV	
4	Kill well, bullheading	9	LWIV	

5	Install and test deep set plug	24	LWIV	
6	Punch/perforate tubing	20	LWIV	
7	Displace tubing and annulus to brine. Retrieve kill hose	21	LWIV	
8	Install downhole safety valve protection sleeve	12	LWIV	
9	Install tubing hanger plug in production and annulus bore	84	LWIV	
10	Pull vertical X-mas tree to surface	18	LWIV	If Xmas tree is horizontal, then it is pulled at the end of phase 1
11	Install corrosion cap and net cover	2,5	LWIV	
Phase 1 – Reservoir abandonment				
12	Anchoring of semi-submersible rig	22	Rig	Anchoring and de-anchoring processes are very slow compared to LWIV and contribute a lot to total operational time.
13	Removal of corrosion cap and net guard	3	Rig	
14	Install BOP and marine riser	36	Rig	No need to run riser if we assume that a vessel has a coiled tubing unit and circulation can be reached through a marine riser hose or through a production line. The approach itself has number of limitations, which will be mentioned in discussions part
15	Pump open tubing hanger production bore plug	3	Rig	
16	Prepare and pull tubing hanger and tubing	48	Rig	LWI vessel does not have an ability to pull the tubing, therefore, it is left in place. As a sealing approach PWC technology is used, but here new Hydrawell tool is involved, which can perforate wash and cement through two casings (tubing and casing in this case). To make a foundation for the cement plug HydraKratos is used.
17	9 5/8“ casing clean out run with bit and scraper	36	Rig	
18	Logging 9 5/8’’ casing	24	Rig	
19	Perforate, wash and cement/ primary plug-	60	Rig	

	(assume the casing is uncemented)			
20	Wait on cement - test plug	24	Rig	
21	Perforate, wash and cement/ secondary plug- (assume the casing is uncemented)	60	Rig	For the secondary plug can be used a thermite seal, which does not require circulation and can be run from the coiled tubing nowadays and from a wireline in prospect.
22	Wait on cement - test plug	24	Rig	
Phase 2 – Intermediate abandonment				
23	Cut and pull 9 5/8" casing	30	Rig	If we assume that surface and intermediate casings are cemented to the top and cement quality is good, then PWC can be used to set a balanced/surface cement plug. However, on subsea wells apart from conductor other casings are usually not cemented to the surface, therefore, Interwell thermite plug might be applicable here, but there are certain concerns that thermite can melt through three or even four casings and for a plug. Another solution can be a SWAT tool, but then the first phase should be performed by a rig, because tubing should be retrieved to install SWAT plug. All of this supports the assumption that each phase separately can be done from a vessel, but not the whole P&A operation in current conditions.
24	13 3/8" casing clean out with bit and scraper	18	Rig	
25	Set drillable bridge plug	9	Rig	
26	Logging 13 3/8'' casing	18	Rig	
27	Place balanced cement plug	24	Rig	
28	Wait on cement - test plug	24	Rig	
29	Pull marine riser and BOP	16	Rig	
30	Install corrosion cap and net cover	2,5	Rig	
31	ROV survey after operation	2,5	Rig	ROV survey can be performed during the last phase due to low operational risks
32	De-anchoring of semisubmersible rig	22	Rig	
Phase 3 – Wellhead removal				

33	Cut and retrieve wellhead	12	LWIV	Use abrasive water jet technology for cutting
34	ROV survey after operation	3	LWIV	Inspect the crater and nearby facilities to check for accidental damages

Table 20 – P&A operational sequence [41]

6.5 P&A discussions

Proposed in the previous section changes in the P&A plan look futuristic in general. However, the separate operations described there might be implemented soon. For instance, HydraWell has already plugged one well in Alaska using coiled tubing, and now they have plans to utilize CT unit on a rig to plug several wells by the end of the year and subsequently try to perform the same procedure from a vessel. Additionally, the company is working at creating a motor for their tools to allow downhole rotation for washing and cementing operations. [40]

Some disadvantages of the proposed plan are:

- Assumption of cemented to surface intermediate casing, which is not very common within subsea wells
- Full circulation can be hardly reached through the riser hose or production line due to pumping limitations
- Limited capability (insufficient jetting energy) of the coiled tubing unit and, therefore, certain plug placing depth limitation
- Cement verification technique after PWC plug setting
- Requirement of a huge deck area to carry all the equipment and crew
- Problems with cementing can occur in highly deviated and horizontal wells

It is important to mention that some of the new P&A techniques generate doubts that they can be used as independent barriers in abandonment operations due to some limitations and drawbacks. On the other hand, industry should consider the combining of several techniques together to produce a sustainable solution. Some of these collaborations might be:

- Utilizing thermite seal as a back-up barrier or as a foundation for another plug

- Squeezing bismuth alloys to damaged tubing area, which allows to leave it in place and set P&A barriers through a vessel
- Use formation as a barrier concept to set a barrier envelope element
- Combining HydraKratos tool and a bismuth-containing tool to set a good foundation for cement plug or act as an independent barrier in the future (both tools can be lowered down from the wireline which makes this combination prospective for riserless abandonment).

Assuming, that efficiency and operation rate for a rig and a vessel are the same, one can observe that 40% of the job can be performed with LWI vessel. Among this are preparatory work and the last phase. There are proposed solutions regarding the reservoir abandonment (first phase) such as PWC and thermite seal. Also, there is a solution for intermediate abandonment (second phase), which is the utilization of the SWAT tool.

For the realization of this huge cost reduction, the industry needs to speed up implementation of recently appeared techniques or to develop a new generation of vessels, which can cope with operations mentioned in table 20 and perform activities mentioned in section 6.2. By doing this, application of vessels for P&A operations would be attractive and open a huge market in the industry.

7 Conclusion

Subsea wells and nearby facilities need to be maintained throughout the whole life cycle of the field to keep production rate on the required level. Inspection maintenance and repair activities of seabed facilities were discussed in the first part of this thesis, and based on the proposed vessel performance improvements it can be stated that most of the challenges and problems appearing during maintenance activities are related to weather, obsolete procedure sequence and delays due to small malfunctions and uncertainties. To minimize non-productive time and increase the performance of subsea IMR operations following recommendations should be considered:

- Up-to-date modernization and review of procedures, processes and task plans
- An increased period between annual inspections if the conditions of the facilities allow for it
- Status of the equipment and spares involved in marine operations should be obtained in advance to prevent delays
- Availability of spare parts and additional details provided by suppliers and service company for ongoing operation
- Perform visual check prior to start the operation and monitor operated subsea facilities with ROV during seabed operations
- Strategy to perform maintenance work can be changed from preventive to corrective and vice versa when it is most economically beneficial

Talking to people from the industry, evaluation of reports and research papers allowed to indicate certain trends in subsea IMR activities and IMR vessels construction process:

- In the years to come, newly constructed vessels will be more complex and technically better equipped and might have handling tower and various integrated systems (i.e. enhanced pumping system) onboard, allowing to perform a wider range of operations.
- Saturation diving will be minimized and might be replaced with ROV operations subsequently due to safety factors, however from the economic perspective diving in some cases is a preferable way of performing interventions.

- Due to development of deep wells and working under Arctic conditions the dynamic positioning class requirement for IMR vessels might be increased to the same as LWI vessels have.

Besides subsea facilities, there are wells itself, which should occasionally be re-entered for maintenance and technical purposes. For subsea wells, it might be performed by a semi-submersible rig anchored to the seafloor and attached to the well by a riser. However, it costs a lot and requires a massive amount of work; therefore, some of the operations are being performed by specifically designed well intervention vessels via pressure control stack. These operations can be improved and can help to reduce downtime by optimizing subsea procedures, as it was stated previously. Some of the primary considerations for improved performance are:

- Time spent for ROV operations should be reduced; for instance, by doing some operations in parallel
- Waiting on weather might be avoided by postponing (if possible) the service for the summer period
- Procedures and programs should be revised and updated, especially regarding communication

At this moment, there are many technologies in development, which will increase the overall efficiency of well interventions and widen the area of their application. Some future applications of intervention assets might be:

- Top hole drilling utilizing coiled tubing
- Riserless mud return and circulation systems
- Subsea controlled rotary

Reaching the aim to develop these technologies and release of new ones will allow vessels to perform some of the heavy work and subsequently replace rigs; however, there is a gap between the development of new LWI equipment and implementing it on the vessels, due to either regulation barriers, or technical limitations of the currently available fleet.

On the last stage of the lifecycle, wells should be permanently plugged and abandoned. P&A is a big topic of recent year discussions, and most of the developments in this sector aim to create a certain technique which will minimize costs and can be applied from LWI vessel and RLWI vessel in prospect. Some of the trends within this branch of the petroleum industry are:

- Reducing milling operations to the minimum and switching to alternative techniques (i.e. HydraWell PWC)
- Development of most demanding technologies such as double casing logging and riserless circulation systems
- Many alternative P&A techniques are at the trial stage right now (i.e. Interwell thermite sealing, bismuth plugs, etc.) and in future can be qualified as acceptable techniques by regulators and authorities. This will open broad prospects in front of utilization of vessels in P&A operations.

As it was previously mentioned there is a wide range of new P&A techniques which can be used separately or in combination with each other. This will positively influence total costs and open broad prospects in front of utilization of vessels in P&A operations.

Optimization of marine operations and enhancement of subsea petroleum activities, in general, is crucial; however, safety should always be on the first place, and none of the HSE requirements can be neglected pursuing the operational excellence.

Bibliography

[1] B. Nyland, "The Shelf in 2017," Norwegian Petroleum Directorate, Stavanger, 2018.

[2] "Petroleum Safety Authority Norway," 21 June 2004. [Online]. Available: http://www.psa.no/. [Accessed 15 April 2018].

[3] "Wintershall," [Online]. Available: https://www.wintershall.com/. [Accessed 20 March 2018].

[4] "Offshore Technology," 11 April 2017. [Online]. Available: https://www.offshore-technology.com/. [Accessed 29 April 2018].

[5] "Gassco," 01 April 2013. [Online]. Available: https://www.gassco.no/en/media. [Accessed 10 May 2018].

[6] J. Speight, Handbook of Offshore Oil and Gas Operations, Gulf Professional Publishing, 2014.

[7] R. v. Flatern, "Defining Intervention: Upstream Maintenance and Repair," *Oilfield Review,* vol. 26, 2015.

[8] L. Fjartoft and S. G, "Success From Subsea Riserless Well Interventions," in *Coiled Tubing and Well intervention Cinference*, Woodlands, 2011.

[9] "FMC Technologies," 2015. [Online]. Available: http://www.fmctechnologies.com/. [Accessed 1 May 2018].

[10] S. Khurana, B. DeWalt and C. Headworth, "Well Intervention Using Rigless Techniques," in *Offshore Technology Conference*, Houston, 2003.

[11] "Wright's," [Online]. Available: http://www.wrightswell.com/wireline-units. [Accessed 11 May 2018].

[12] "The Institute of Materials, Minerals and Mining," [Online]. Available: http://www.iom3.org/. [Accessed 5 May 2018].

[13] J. Aasen, *Well Intervention and Permanent Plugging,* Stavanger: University of Stavanger, 2017.

[14] "National oilwell Varco," [Online]. Available: http://www.nov.com/Segments/Completion_and_Production_Solutions/. [Accessed 13 May 2018].

[15] R. Christie, L. Zhanke, R. Stanley, M. Torregrossa, A. Zheng and L. Zsolt, "Monitoring Coiled Tubing Fatigue Life," *Oilfield Review,* vol. 27, no. 1, May 2015.

[16] "Subsea 7," [Online]. Available: https://www.subsea7.com/. [Accessed 18 March 2018].

[17] "DeepOcean," [Online]. Available: https://deepoceangroup.com/. [Accessed 21 March 2018].

[18] "Infinity Oilfield Services," [Online]. Available: http://infinityoilgas.com/integrated-support. [Accessed 20 May 2018].

[19] *NORSOK Standard D-010 rev.4: Well integrity in drilling and well operations,* Lysaker: Standard Online AS, 2013.

[20] K. K. Fjelde, *Introduction to P&A,* Stavanger: University of Stavanger, 2017.

[21] K. Chopra, "Marine Insight," 7 October 2017. [Online]. Available: https://www.marineinsight.com/. [Accessed 13 May 2018].

[22] O. Kratz, "Well Intervention Overview," Helix.

[23] FMC Technologies, Personal Handbook for Vega, Kongsberg: Industriell Dokumentasjon, 2010.

[24] Wintershall Norge AS, *Internal documentation,* Stavanger.

[25] J. Chin and E. Fakas, "Evaluations of Surface And Subsea Pig Launching Systems," in *The Fourteenth International Offshore and Polar Engineering Conference*, Toulon, 2004.

[26] *Fighting Scale—Removal and Prevention,* vol. 11, Oilfield Review, 1999.

[27] "Subsea Control Module," [Online]. Available: http://www.oilfieldwiki.com/wiki/Subsea_Control_Module_(SCM). [Accessed 9 June 2018].

[28] F. Moeinikia, K. K. Fjelde, J. Sørbø, A. Saases and T. Vrålstad, "A Study of Possible Solutions for Cost Efficient Subsea Well Abandonment," in *International Conference on Ocean, Offshore and Arctic Engineering*, St. John's, 2015.

[29] L. Dahmani and L. Hynes, "Enhancing Well Construction for More Efficient Well Abandonment," in *Asia Pacific Oil & Gas Conference*, Jakarta, 2017.

[30] K. Fredagsvik, *Formation as Barrier for Plug and Abandonment of Wells,* Stavanger: University of Stavanger, 2017.

[31] E. Fjær and T. G. Kristiansen, "Activated Creeping Shale to Remove the Open Annulus," in *P&A Seminar 2017*, Stavanger, 2017.

[32] M. Khalifeh, A. Saasen, H. Hodne and T. Vrålstad, "Techniques and Materials for North Sea Plug and Abandonment Operations," in *Offshore Technology Conference*, Houston, 2013.

[33] BiSN, "Wel-lok M2M," in *P&A Forum Stavanger*, Stavanger, 2017.

[34] BiSN, "Wel-lok M2M Sealing Solutions," [Online]. Available: https://www.bisn.com/. [Accessed 30 January 2018].

[35] "Thermite makes P&A right," 23 May 2016. [Online]. Available: https://www.innovoil.co.uk/single-post/2016/05/23/Thermite-makes-PA-right-1. [Accessed 2 May 2018].

[36] *Rig-less Plug and Abandonment.* [Film]. Norway.

[37] Interwell, "Rig-less Plug and Abandonment," 23 March 2018. [Online]. Available: http://www.interwell.com/. [Accessed 28 May 2018].

[38] HydraWell, "HydraHemera," [Online]. Available: https://www.hydrawell.no/product/hydrahemera/. [Accessed 9 June 2018].

[39] *Perforate and Wash Tool.* [Film]. Norway.2016.

[40] M. Myhre, Interviewee, *HydraWell P&A.* [Interview]. 1 June 2018.

[41] Acteon Group Ltd, "Acteon Companies Claxton And OIS Improve Decommissioning Technology To Deliver Subsea Well Abandonment Campaign," 7 October 2015. [Online]. Available: https://www.oilandgasonline.com/doc. [Accessed 30 June 2018].

[42] Claxton, "Suspended Well Abandonment Tool," [Online]. Available: http://claxtonengineering.com/products-services/decommissioning. [Accessed 30 June 2018].

[43] F. Moeinikia, K. K. Fjelde, A. Saasen, T. Vrålstad and A. Øystein, "Evaluating Cost Efficiency of Rigless P&A for Subsea Multiwell Campaign," in *Drilling Conference and Exhibition*, Fort Worth, 2014.

[44] DNV GL SE, *Rules for Classification and Construction,* Hamburg: DNV GL SE, 2016.

[45] "Island Offshore Subsea," [Online]. Available: http://www.iosubsea.no/our-services/light-well-intervention. [Accessed 28 May 2018].

Appendix

Appendix A – Dynamic positioning system

Dynamic positioning (DP) is a computer-controlled system, which automatically maintains position and heading of a vessel by using its own propellers and thrusters. Position reference sensors, combined with wind sensors, motion sensors and gyrocompasses, provide information to the computer pertaining to the position of a vessel and the magnitude and direction of environmental forces affecting its position.

A DP system consists of components and systems acting together to achieve sufficiently reliable position keeping capability. The complete installation necessary for dynamically positioning vessel comprises [44]:

- power system;
- thruster system;
- DP control system;
- independent joystick (not for DP 0 class).

Most of the regulations distinguish four major types of dynamic positioning systems. Vessels in the petroleum industry are most likely to have DP class 2 or 3. Table 21 shows the differences between the classes.

Class of dynamic positioning system	Functional requirements
DP 0	Ability to keep their position at least in automatic mode.
DP 1 (DP I)	Ability to keep their position at least in automatic mode and joystick mode. Loss of the position may occur in the event of a single fault.
DP 2 (DP II)	Ability to keep their position after a single failure in an active component
DP 3 (DP III)	Ability to keep their position after a single failure in an active or static component. This applies also for the total loss of the equipment in one compartment due to fire or flooding.

Table 21 – Dynamic positioning classes [44]

Appendix B – Benchmarking

Operation	Place	Vessel arrival	Vessel departure	Stop production	Start production	Shut-down time	Downtime	Total operational time
CM replacement	Field A, N-1	21/09/16 04:00	23/09/16 15:18	20/09/16 09:27	23/09/16 16:52	79,42	6,67	51,37
CM replacement	Field A, C-8	25/03/14 12:25	26/03/14 22:05	24/03/14 00:38	26/03/14 22:56	70,3	0	33,68
CM replacement	Field A, N-1	17/09/13 20:24	19/09/13 21:10	17/09/13 23:38	19/09/13 20:00	44,37	1	48,77
CM replacement	Field A, N-1	05/09/11 04:19	07/09/11 02:42	03/09/11 16:11	07/09/11 04:02	83,85	2,66	46,53
SCM replacement	Field A, S-10	23/09/16 18:02	24/09/16 14:10	23/09/16 17:33	25/09/16 02:37	33,07	0	20,13

Operation	Place	Duration in hours	Template N	Template C	Template S	Average per template
Annual ROV inspection 2016	Field A	18,35	n/a	n/a	n/a	6,1
Annual ROV inspection 2015	Field A	11,37	2,58	4,08	4,7	3,8
Annual ROV inspection 2014	Field A	11,18	4,53	3,27	3,38	3,7
Annual ROV inspection 2013	Field A	11,02	1,8	1,85	7,37	3,7

Table 22 – Duration of IMR activities [24]