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Høgskulen  
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# MASTER'S THESIS

## CESSATION WORK FOR DEEP WATER PIPELINES

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Name of Master program: Master of Maritime Operations

Department/Institute/Program: Maritime Studies

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I confirm that the work is self-prepared and that references/source references to all sources used in the work are provided, cf. Regulation relating to academic studies and examinations at the Western Norway University of Applied Sciences (HVL), § 12-1.



## Abstract

The oil and gas fields on the Norwegian Continental shelf are getting older and older. Several oil and gas installations will have lasted their lifetime in the next few years. Some rigs have already been taken out of service, and the finishing work varies from project to project. As of today, the principle is that each case is treated individually. For this reason, among other things, evaluating what should be done with the facilities, including subsea pipelines are time-consuming.

The topic for this thesis was motivated and carried out in collaboration with Equinor, Field Life Extension (FLX) department, which is also responsible for planning and execution of decommissioning projects in Equinor.

In most cases, pipelines remain on the seabed. For a few cases, they are taken ashore. The possibilities are many, but the method that should be used as a best practice have not been determined. Advisor Tor Inge Fossan suggested therefore writing about this topic. It is agreed that one of the most critical factors in the report will be that solutions must be environmentally friendly while at the same time minimizing the risk of adverse events in later times.

During the autumn of 2021, a pre-study was conducted as preparatory work for the master's thesis. The primary focus of this study was to list possible philosophies for pipelines at the seabed when the service time of the offshore field is ended.

What laws and rules say about the issue is the basis for the ideas presented in this report. There are two very dissimilar methods, one of which is more relevant than the other.

The first proposal is to make the pipe corrode away. Several methods are proposed within this theme to accelerate the corrosion time, but calculations show that the corrosion time is slow. Methods are presented that, among other things, affect the anode/cathode ratio, and it is suggested to apply current or power to reduce the corrosion time.

The second idea deals with a completely different topic. Here it is proposed that a collapsed pipe will be to a lesser inconvenience to other sea users than an intact pipe. It can not be said with certainty that the pipe will collapse perfectly and thus be completely flat, so covering with gravel is also proposed. If it becomes necessary to cover the line afterward, it is considered more reasonable to cover a collapsed pipe. In this part of the report, both manual calculations and analyzes are performed in the ANSYS program.

Before a concluding discussion and conclusion, a comparison is made between existing and proposed methods. This comparison is made in terms of costs and emissions to air.

***Keywords: Offshore cessation work, subsea pipelines decommissioning, corrosion, pressure calculations, finite-element modeling, ANSYS***

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This thesis was written by Jill Hermansen as a part of a master's degree at the Maritime Department at the Western Norway University of Applied Sciences (HVL) in Haugesund. This is the final part of the study program Maritime Operations with the specialization in Offshore and Subsea Operation. This study program is a collaboration between HVL and University of Applied Science in Germany.

First, I want to thank my two supervisors from HVL so much for their commitment. They have guided me in the right direction and given me good tips for literature in addition to my own experience in the offshore industry. Professor Jens Christian Lindaas has been the primary supervisor and has taken the time to give advice and tips throughout the assignment. Professor Ove Tobias Gudmestad offered early to be a secondary supervisor as he has worked at Equinor for many years and worked with subsea pipelines. Ove Tobias has come up with essential factors that should be considered in the thesis. Furthermore, I would like to thank Zhenhui Liu, who has helped me immensely with the analysis program.

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## Notation

### Abbreviations

API	American Petroleum Institute
CP	Cathodic Protection
CTE	Coal Tar Enamel
DNV	Det Norske Veritas
ECA	Emission Control Areas
EF	Emission Factor
ERW	Electric Resistance Welding
FBE	Fusion Bonded Epoxy coating
FLX	Field Life Extension
HFO	Heavy Fuel Oil
ISO	International Organization for Standardization
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MNOK	Million Norwegian Kroners
NOK	Norwegian Kroners
NORSOK	The Norwegian shelf's competitive position
OSPAR	Oslo Paris Convention
PIG	Pipeline Intervention Gadgets
PP	Polypropylene
ROV	Remote Operated Vehicle
SCE	Saturated Calomel Electrode
SPTS	Statoil Pipe Tracking System

### Variables

A	Anode area
D	Pipe outer diameter
$D_{\max}$	Maximum Diameter
$D_{\min}$	Minimum Diameter
E	Elastic modulus
$F_C$	Faraday's constant
$f_0$	Ovality, safety factor
g	Gravity

$h$	Height
$i_{\text{corrosion}}$	Corrosion current density
$M$	Molar mass
$m_p$	Plastic moment capacity of the pipe wall
$n$	Hardening exponent in Ramberg- Osgood's model
$O_0$	Ovality
$P$	Pressure
$P_c$	Collapse pressure
$P_e$	External pressure
$P_{el}$	Elastic collapse pressure
$P_i$	Internal pressure
$P_{pl}$	Plastic collapse pressure
$P_{pr}$	Propagation pressure
$t$	Wall thickness
$w$	Weight
$z$	Number of electrons in the reaction equation for the anodic reaction
$\alpha_{\text{fab}}$	Fabrication factor
$\nu$	Poisson's ratio
$\Delta s$	Change in length
$\Delta t$	Change in time
$\sigma_y$	Yield strength
$\rho$	Density
$\delta$	Pipe deformation, dent depth

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# 1 Introduction

## 1.1 Background and Motivation

Subsea pipelines are used in large parts of the world to transport oil and gas. In the book "Pipelines in deep water," published in 1974, it was written that there were about 400,000 km of pipelines on the seabed for oil and 1.5 million km of pipelines for gas transport installed worldwide [1]. Since then, a significant number of new oil and gas fields have been developed worldwide, and the number of kilometers of subsea pipelines has increased significantly.

Below is an own-made illustration of pipelines owned by Equinor. Figure 1 includes the installation year and the pipe's length, measured in kilometers.

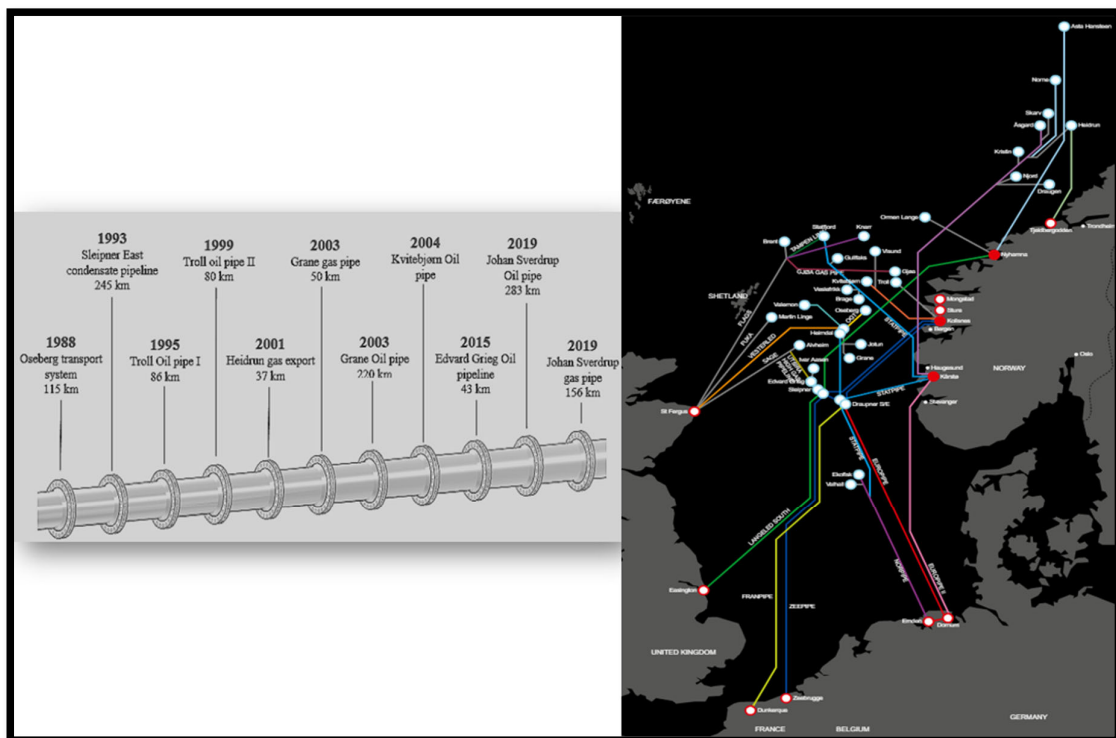


Figure 1 Overview of Equinor's subsea pipelines [2]

All pipelines laid on the seabed will go out of service at a given time. However, what method is followed when the pipelines are no longer in use is not concluded.

Equinor has established a department that will become specialists in operating oil and gas fields in the late phase. The department is, as mentioned, called FLX (Field Live Extension). Becoming good at operating platforms nearing the end of service time also includes planning

what to do with the installation when the service life is over. It will also include what should be done with the pipelines installed on the seabed.

The current method is to evaluate each case individually, where one of the main problems is whether the pipelines can be to the detriment of other sea users. Such problems result in stretched planning phases each time a pipe goes out of service. Usually, the options are to leave the pipe in situ, dig it down, or lift it.

This master's thesis will take a deep dive into ideas and methods that have not been found information about before. This master's thesis will thus look at additional methods that can be used on a more general basis to avoid as much as possible that each pipeline is studied individually. In addition, the methods presented will focus on the pipeline not being to the detriment of other sea users. Furthermore, it is desirable to present environmentally friendly and affordable solutions in terms of costs.

## 1.2 Objectives

The main aim of the research is to develop an environmentally friendly and cost efficiently method for pipelines at the seabed after service time for the offshore field. This includes a study of several different own ideas. The first part of the report contains essential information used further in the report regardless of which ideas are presented. The second part of the report studies own ideas. In addition, a summary of existing methods for completing work for pipelines is presented.

Presented thesis seeks to answer the following research questions:

1. How will a reverse cathodic method affect the corrosion process of the pipeline?
2. What other methods may be relevant?
3. Which method will be the best in the long run, in terms of the environment and the costs the method will entail?

To be able to answer selected research questions in the highest possible relevance for the industry, boundaries have been set up, and presented, in the next chapter. In addition, a preliminary project has been carried out as research. This project provides a reasonable basis for existing laws and regulations and the methods for completing existing work. A summary of this preliminary project will be presented later in the report.

The two ideas presented different topics, but the pipeline will be left at the seabed in both suggestions. It is first investigated whether it is possible to get the pipe to corrode away faster



than it would usually have done if it had remained on the seabed. If this is possible, it is thought that the pipeline will not be to the detriment of other sea users. In addition, it is believed that significant changes will then be avoided in the area where the pipeline is located.

The next suggestion is to make the pipe collapse. If the pipe flattens out, significant changes in the area will be avoided, and the pipe will not be to the detriment of others.

### 1.3 Limitations

The following research is limited to the Norwegian Continental Shelf due to different regional guidelines and laws for offshore operations. The report will focus on larger steel pipelines as it is assumed that there are good enough solutions for smaller steel and composite pipes. It is said that there are good enough methods for smaller pipes because the reverse reel lay method has been tried out and works well for pipes smaller than 16 inches. Therefore, the main focus will be on preliminary rigid pipes size bigger than 16 inches. In addition, the report will only be valid for pipelines above the seabed, meaning that it will not be valid for buried pipelines, which is assumed not to be detrimental to other sea users.

### 1.4 Scope

Chapter 2 presents the research method used in the report. This section includes a justification for the research method, essential criteria emphasized in the report, and a description of how the data collection is performed.

Chapter 3 summarizes the preparatory work done in the autumn of 2021 [3]. This work was submitted as a semester assignment and addressed several important topics that will form the basis for the possibilities for the final work for the subsea pipelines.

Chapter 4 presents imperative information regarding the pipelines installed at the seabed. Here the focus is on the methods used to protect the pipelines from corrosion. The corrosion protection provides a foundation for which ideas will be practically conceivable to implement later in the report. Additionally, some pipeline data are used as a baseline in the report.

Chapter 5 focuses on the reverse cathodic method. The reverse cathodic method is the first method proposed as completion work in connection with the pipelines on the seabed. This chapter uses introductory chemistry to understand what corrosion is and how it occurs. Calculations of how much pipe corrodes annually are performed before materials that may be

relevant are presented. Furthermore, the relationship between anodes and cathodes in seawater is presented.

Chapter 6, "Second idea, force the pipe to collapse," describes an entirely different idea than the first. Here, a deep dive is taken into what is needed to force a pipe to collapse. The collapse, differential, and propagation pressure are crucial elements in this chapter. Furthermore, hand calculations are evaluated against calculations in ANSYS.

Chapter 7 deals with presenting costs and emissions to air for five different methods. The two methods presented in the report are included, and three existing methods are included. The methods' costs and emissions are compared further in the discussion chapter.

Chapter 8 is the complete discussion of the report. Several sub-discussions have occurred during the report, so this chapter links these discussions together. In addition, the cost estimates and emission estimates are discussed and compared.

Chapter 9 is the conclusion of the report. Here, it is recommended, among other things, what should be worked on further, and conclusions are drawn about the work that has been done for the two methods the report has presented.

## 2 Research method

### 2.1 Research approach

The report includes qualitative and quantitative analysis. The research objective is to establish an optimal principle when it comes to removing or leaving the pipelines at the seabed.

Establishing such a principle has been vital to keeping a high focus on the validity and reliability of the attained results. The validity of the research was obtained and kept by focusing on finding other alternatives which could explain the results. Furthermore, the validity was obtained through discussing with several experienced professionals from different departments within Equinor and HVL.

On the other side, reliability has been a major focus area. Without focusing on the reliability, the conclusions would have been worthless. Some rules have been followed to keep high reliability throughout the whole report. The first rule has been that all sources must have a basis for being trusted. This rule has been followed as the most critical parameters in the report come either from standards, laws, literature books, or internal documents in Equinor. The second rule is that no sources should be used in this report if only one source has been found that informs about the topic. Similar literature has been found for each source, and the literature has since been compared. Extremely much time has been spent on comparing the sources. If the calculations or other information in the report are incorrect, this report will not have any value either.

### 2.2 Data collection

Different types of data required are written below:

- Laws and regulations: There are usually several versions of the same standard in connection with laws and regulations. There are different versions depending on which sector is relevant. Based on this, standards have been chosen that will be most relevant in this case.
- Secondary or existing data: data such as conventions, guidelines, and standards have been collected using "document reviewing" through internet searches.
- Internal documents have been used to make the report as relevant as possible for Equinor. Therefore, it is based on pipes similar to the pipes Equinor owns. In addition, internal sources from Equinor have been used to calculate costs for various

operations. This is because no discovery of this type of information has been made public.

All literature searches are marked with sources. Standards such as DNV GL and API are some of the sources that are used diligently. In addition, textbooks are referred to in several places as credible. Oria, a search engine controlled by HVL, has also been used to find relevant subject matter for the report. Finally, several sources from Equinor's internal document system have been used.

### 2.3 Aids and programs

It has been chosen to use several aids and programs in the thesis to make this report as relevant and reliable as possible. The information provided regarding relevant pipelines and their parameters is taken from internal systems in Equinor. Some of these are STID and SPTS. STID is a program where documents are stored. Here is the report made after installing the pipe mentioned in this report. SPTS is a program that contains the most critical parameters of pipelines, such as lengths of protective layers, with more.

For all illustrations made in the report, the program Paint 3D is used.

For some of the calculations, programming has been done in Excel.

ANSYS is used to investigate the collapse of pipes.

### 3 Preliminary work

As mentioned earlier, a preliminary project was written on the subject Profile Project in the autumn of 2021 [3]. The project went in-depth on several topics. Some of the themes were about what laws and regulations exist in Norway and internationally. Furthermore, an important topic has been preparation work before the pipelines can be laid or taken up as described. In addition, existing methods were described. In the chapter on existing methods, the method leaves in situ or removing the pipeline were studied. In the last part of the report, own ideas were briefly discussed. The own methods and further work on these methods will be a focus in this report. This chapter will summarize the most critical elements from the report in Profile Project.

#### 3.1 Existing regulations and laws

The two guidelines that will form the basis of this report will be the Petroleum Activities Act and OSPAR (Oslo-Paris Convention). It is chosen to base solutions on what is stated in these two guidelines because the report is limited to the Norwegian continental shelf. The report written in Profile Project also described other standards internationally [3].

In 1992, the OSPAR convention was published and states, among other things, that each case concerning finishing work for pipelines must be studied individually. The evaluation must include all types of risks in work done, and the state must approve this in advance of the work.

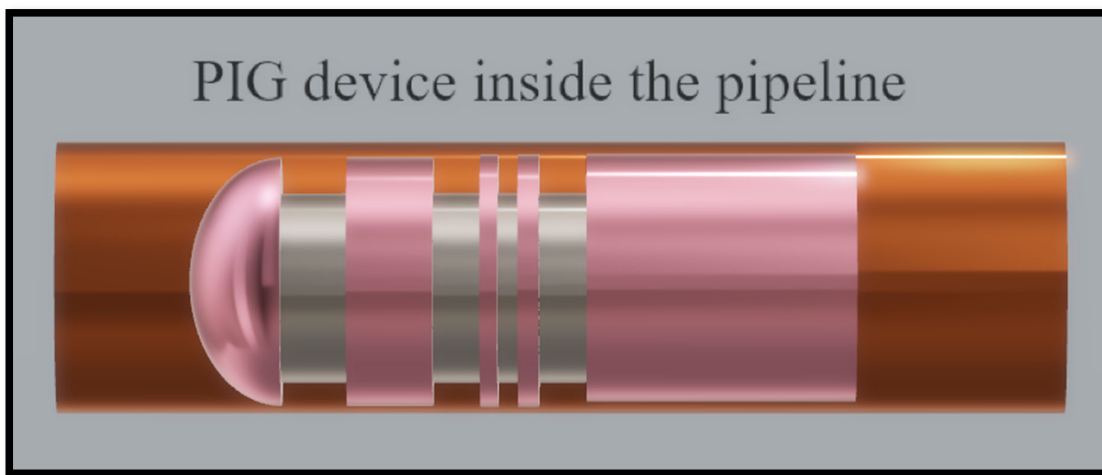
In 1997, the Petroleum Activities Act was published. Here, too, it is required that the state must approve each case.

Common to the guidelines is that if the pipeline remains on the seabed, the owner, who is Equinor in this case, will still be responsible for the pipeline throughout the life of the pipe. It is assumed that this will include inspection work and responsibility for unwanted incidents such as hazardous waste at sea or that trawls get stuck in the pipeline to maintain safety. This responsibility includes all risks that other sea users may be exposed to.

### 3.2 Preliminary pipeline flushing

Both laws from the previous chapter clarify that the pipelines must be cleaned regardless of what is done with the pipelines in the cessation work. Cleaning the pipeline will be incredibly important in any case.

There are several cleaning methods. The methods described in the Profile Project report are pipeline intervention gadgets (PIG) and flushing [3]. A PIG is a device passed through the pipe to clean or analyze the pipeline. The PIG is transported through the pipeline using liquid under pressure, often seawater. An illustration is made to illustrate the PIG device in Figure 2. The pink illustrates the PIG, while the orange or brown is the pipeline itself.



*Figure 2 PIG Illustration*

Flushing creates a turbulent flow of the cleaning fluid inside the pipe. The fluid will mainly be water. The turbulent flow inside the pipe cleans the walls of the pipe.

Since cleaning pipelines is not one of the tasks Equinor has significant questions about, it is chosen not to detail this in this report. However, it is recommended to look further at the risk of dangerous gas or liquid forming in the pipe when it corrodes if the pipe remains on the seabed [3].

### 3.3 Existing methods

Submarine pipelines have been taken out of service in the past, and there are several existing methods for removing them and leaving them on the seabed. Therefore, this chapter will summarize the pipelines that remain on the seabed and the methods used when removing the pipelines.

### 3.3.1 Leave in situ, partially remove

Leave in situ or partial removal of the pipelines are the most used methods on the Norwegian shelf today. The methods are used to prevent the pipe from being to the detriment of other sea users. In cases where the pipe remains on the seabed, it is common to either cover the pipe or dig the pipe down.

Masses covering the pipes are often shingles. Overfilling the pipe with pebbles is relatively expensive but necessary in some cases. Backfilling is an appropriate method if it is impossible to dig the pipeline down for topographical or other reasons. If it turns out that the pipe can be to the detriment of others, either the trenching or burial methods are typically used. On the Norwegian shelf, it is documented that both methods have been used [3].

Several types of equipment can be used for performing trenching and burial. This report does not go into every method, but some of the most common methods are mentioned. The methods used depend to a large extent on the geological structure of the seabed in the area. One of the methods that can be used if the seabed is made of sand, is a self-propelled burial sled. Furthermore, a hydraulic dredge can be used. This method can be used when using different pumps, depending on the relevant sea depth. In addition, a method called jetting can be used. Jetting uses high pressure of water and air to push the sand away from the seabed. In this way, gravity moves the pipe further down into the seabed [3].

### 3.3.2 Remove the pipeline

In contrast to leaving the pipelines on the seabed, some methods can remove the pipelines. Removing is done less often than leaving the pipes for larger rigid pipes.

Removing pipelines requires large amounts of resources. It requires, among other things, vessels, and personnel for lifting, cutting, and transporting the pipelines. There are plenty of cutting methods available today, and some of them use water or wire, for example, high-pressure water or cutting wire. Other methods use hydraulics or other pressurized tools [3].

The methods reverse reel lay or reverse S-lay can remove pipelines. Both methods are used to install the pipelines. The only difference is that the various operations are performed in the opposite order.

Figure 3 and Figure 4 present the two methods relatively.

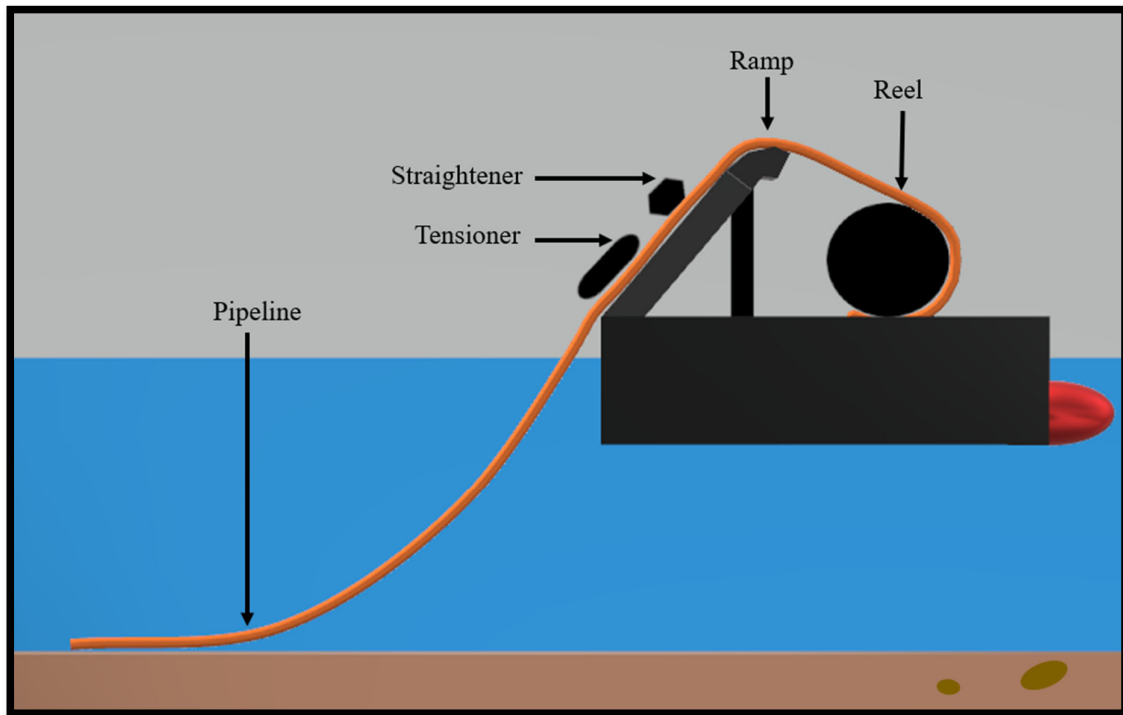


Figure 3 Reel lay illustration [4]

The reel lay method involves cutting the pipe into suitable lengths before pulling it up on the ship's reel. The S-lay method is more suitable for larger pipe dimensions. When using this method, the pipe will be pulled up from the seabed at the same time as the vessel is propelling. The pipe is cut either on the seabed or onboard the ship. After that, the pipe spool is pulled up on a firing line installed on the vessel [3].

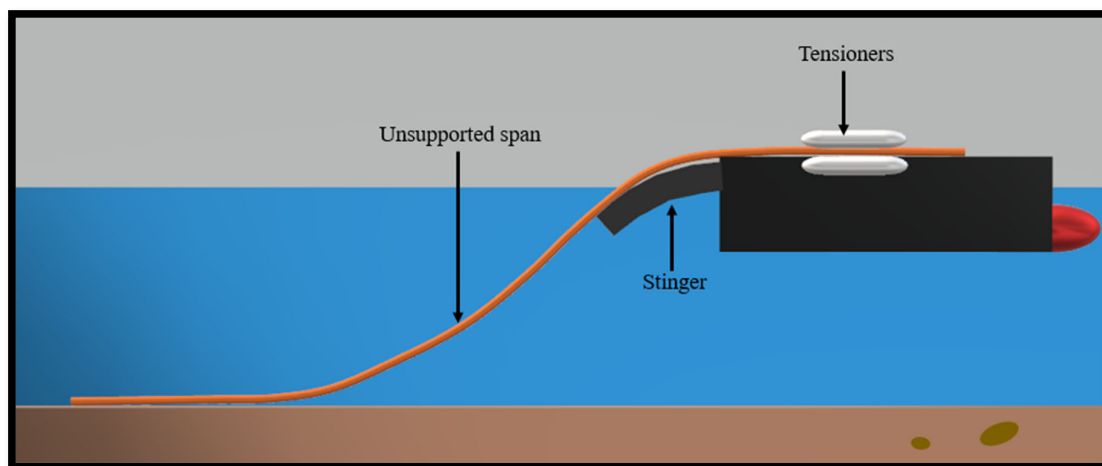


Figure 4 S-Lay illustration [3]



As shown in the illustrations above, the pipeline will be subjected to large forces by removing it. At the end of its service life, the wall thickness should be assumed to be thinner due to corrosion and other operational conditions. Then the pipe will be weaker than it was when it was installed. It will be essential to consider whether the pipe will be plastically deformed due to the forces in decommissioning. In addition, dragging up the pipe will increase the risk of personal injury and damage to the vessel. These risks must be considered when choosing this type of removal method.

In addition to the forces that must be considered, there will be a demand to use the s-lay method for pipes coated with concrete or other protective layers that make the pipe stiffer.

Instead of using either reverse installation method, it is also possible to cut the pipe into suitable lengths and lift them. This method will be less dependent on the pipe size because it can be cut so that the weight does not become too high. Remote-operated vehicles can help cut the subsea pipeline, and a surface vessel with an installed crane is required to lift the pipe spools. If several kilometers of pipelines are removed, this will be a relatively time-consuming and expensive method but can be an effective method if more minor parts of the pipeline are removed [3]. One of the most significant drawbacks of this method, as with the other methods, is that the risk of damage to surface vessels and personnel is higher than leaving the pipe on the seabed.

### 3.4 Conclusions from preliminary work

From the report, some important points must be considered in this report [3]. These conclusions are presented in this part of the report.

The first conclusion is that it is not reasonable to assume that the current laws and rules will not change in the next few years. The laws are old, and with the green shift, it is reasonable to assume that the current rules can quickly become outdated. Regardless of the outcome of this report, environmentally friendly solutions should be looked at further.

The report further concludes that if existing solutions are used, the environment, the risk of damage to the environment, equipment, and people should also be considered.

Finally, it is concluded that if methods are chosen that involve leaving the pipe on the seabed, it will be a great advantage to dig the pipes or protect them so that they will lie stably and safely for the entire life of the pipe.

Several methods were also presented that can be looked at in more detail to complete work for the pipelines. Seven different methods are mentioned. One of the solutions is to continue using the pipelines for other purposes, and another is to sell the pipeline. This method is not studied further here as there are already projects within Equinor on this. In addition, there will still be a question mark behind what should be done with the pipelines after they have been used for something else when the time comes.

The following methods presented are reverse-cathodic protection and force the pipe to collapse. These methods will be looked at in more detail in this report.

Other methods are to make artificial reefs or to make the pipeline floatable. These methods are not presented in the report, but the latter is considered relevant to look at further if there is reason to believe that the laws will change in the coming years. In addition, making the pipeline floatable should be considered if it is desirable to be a leader in the green shift regarding what is done on the seabed [3].

## 4 The installed pipelines

This chapter will present information about the pipelines that will be significant later in the report. This information will be fundamental to all methods and ideas presented.

### 4.1 Corrosion Prevention and coatings

Pipelines installed on the seabed are primarily exposed to corrosion. Before the pipelines were installed, measures were taken to delay the corrosion process to prevent corroding. This delay is called corrosion prevention.

Pipelines are coated as primary protection against corrosion. As it can be challenging to have an overview of the condition of the coating, it is common to install a secondary system as well. The secondary system is, in many cases, cathodic protection (CP) [5].

An exterior coating usually covers pipes installed on the seabed. This cover is a coating that will protect the pipe for several reasons. Perhaps the most important reason, at least the most important reason for this report, is that the coating protects against corrosion. Later in the report, three parameters that depend on each other to create corrosion will be listed. One of the parameters was that there must be electrical contact between the materials. Therefore, one of the essential properties of the coating will be electrical insulation.

There are several different types of coating, such as tape wrap, asphalt, coal tar enamel, and more. This report focuses on fusion bonded epoxy coating (FBE), asphalt, and coal tar enamel, as internal documents within Equinor show that several of the pipelines have this coating. Document C077-C-F-RE-006 [6], applicable to pipelines on the Sleipner field, includes FBE as a coating. Other data retrieved from the same document shows all coating data from one of the flowlines. This overview is shown in Table 1 below.

*Table 1 Coating types*

Number of layers	Coating type	Exposed [mm]	Density [kg/m <sup>3</sup> ]
1	FBE	0,3	1300
2	Adhesive	0,3	900
3	Solid PP	4,7	900
4	PP Foam	30	680
5	Solid PP	3	900
6	PP Foam	30	680
7	Solid PP	4	900

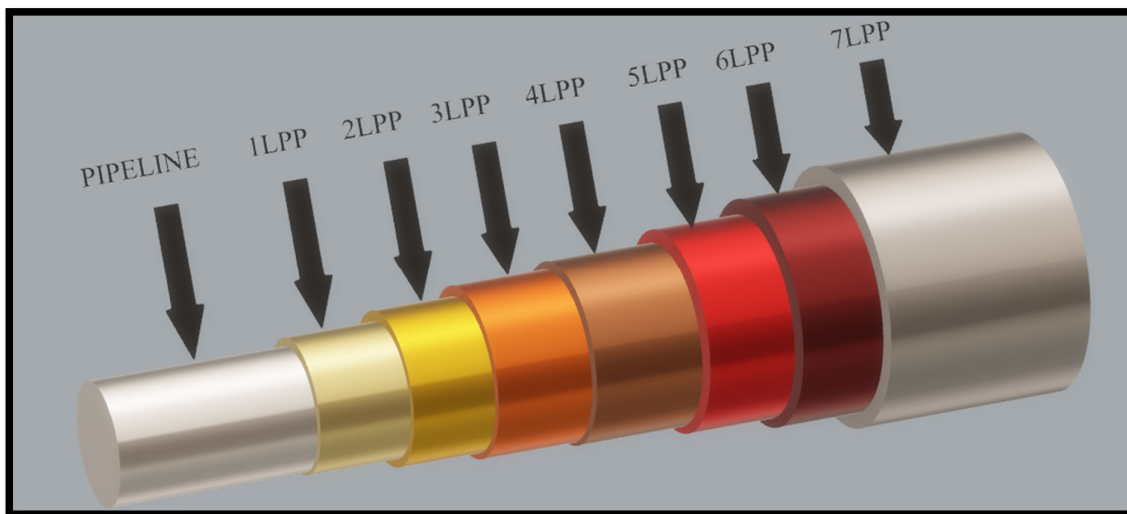
FBE is a substance used to increase the corrosion resistance of materials. The coating is primarily used for seabed pipes due to the coating's density and protection against both the environment and corrosion cells [7].

An adhesive is used on the outside of the FBE coating before applying solid polypropylene (PP). Solid PP has many of the same benefits as FBE. Examples of these are high-density and insulate well against corrosion cells. In addition, the PP can withstand relatively high temperatures [8].

According to Norway's public reports, a typical asphalt coating consists of 14% asphalt, 1% asbestos fiber or fiberglass, 65% sand, and 20% limestone [1].

CTE (Coal Tar Enamel) is a blend material used to coat pipelines. Mixtures are primarily based on polymer. The secondary materials added to the plastic provide CTE with the properties necessary to maintain corrosion resistance. In addition, this type of coating insulates excellently against electricity and water. CTE is used under the concrete or asphalt layer. Recently, it has been shown that this substance is carcinogenic, and it has therefore been banned for use in several places.

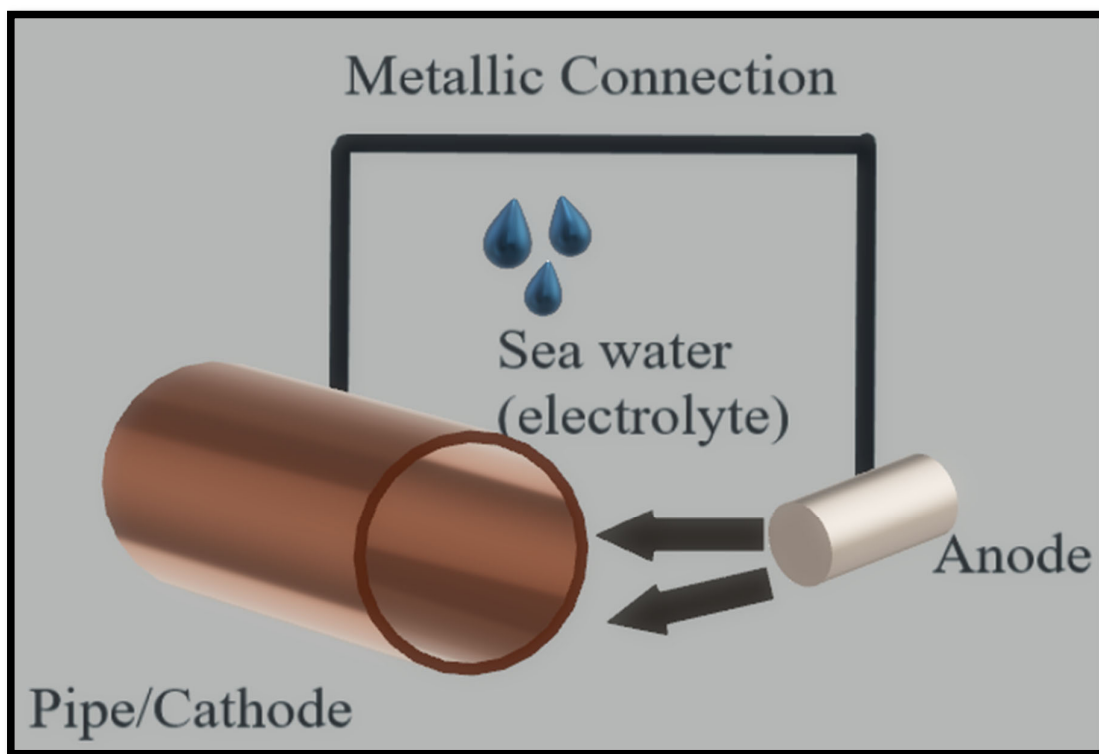
Until now, emphasis has been placed on the corrosion resistance of the coatings presented in Chapter 3. An offshore pipeline at several hundred meters of sea depth is not only corrosion that the coatings must protect against. Temperature and pressure are also a challenge for such pipelines. Substances such as PP are an example of incompressible coatings [9]. To show what is meant by 7LPP, an illustration of this has been made below, in Figure 5.



*Figure 5 Illustration of polypropylene layers*

As shown in the illustration in Figure 5, the numbers reflect the numbers listed in Table 1.

Cathodic protection is used, as mentioned earlier, as secondary protection against corrosion. Cathodic protection aims to move the corrosion area from the pipe to a sacrificial anode. A sacrificial anode can be of different materials. However, for the method to work, the sacrificial anode must be of a less noble material than the steel the pipe is made of. The most common materials for sacrificial anodes when the book *Deepwater Pipelines* was published in 1974 correspond to today's materials, magnesium, zinc, and aluminum [1]. It is assumed that the anodes installed are of the Al-Zn-In type, a mixed material to optimize corrosion resistance. In Figure 6, a cathodic protection process is presented.



*Figure 6 Cathodic protection*

Data on the anode types have been obtained from the same document. This overview is presented in Table 2.

Table 2 Anode data

Parameter	Anode type C, BBA-366
<b>Pipeline Diameter</b>	20 inches
<b>Total length of pipeline</b>	200km
<b>Anode type</b>	Bracelet
<b>Number of anodes</b>	120 every third km
<b>Minimum anode length</b>	500 mm
<b>Minimum anode net weight</b>	56 kg
<b>Anode material</b>	Al-Zn-In
<b>Anode thickness</b>	42 mm

#### 4.2 Pipe parameters

This chapter looks at a 20-inch pipeline and its parameters. All data presented in this chapter are taken from the internal document in Equinor [10], except parameters 6-9 [11]. For parameters 7-10 in Table 3, it is assumed that X65 carbon steel will have the same properties as X60 carbon steel. This chapter presents these parameters to make calculations later in the report.

Table 3 Pipeline parameters

Pipe Parameters, API 5L X65 Carbon Steel		
<b>1</b>	Pipe Diameter (D), (+0,75%, -2%)	508 mm (20 inches)
<b>2</b>	Wall Thickness (t)	17,5 mm
<b>3</b>	Pipeline Air Weight	384,6 kg/m
<b>4</b>	Water dept (approximately)	310m
<b>5</b>	Design pressure	74,3 bars (g)
<b>6</b>	Elastic modulus (E)	210 GPa
<b>7</b>	Poisson's ratio ( $\nu$ )	0,3
<b>8</b>	Yield strength ( $\sigma_y$ )	413 MPa
<b>9</b>	Hardening exponent in Ramberg- Osgood's model (n)	12
<b>10</b>	Ultimate stress	517 N/mm <sup>2</sup>

## 5 First option, reverse cathodic protection

Before the voltage range and the chemical, itself are presented, a short presentation of corrosion and how corrosion occurs is presented. As the relevant pipelines are installed on the seabed, seawater will be an essential factor further in the project.

Corrosion can occur in various types, such as galvanic corrosion, pitting corrosion, and the like. Common to all types of corrosion is primarily an electrochemical process, where the metal reacts with the environment. The electrochemical process causes the deterioration of the metal.

### 5.1 The idea

The idea in this section is about creating corrosion instead of avoiding corrosion. The idea is to speed up the corrosion time of the pipelines. In this way, the time the pipe is to the detriment of other sea users will be shorter. Before investigating this further, it is essential to point out that this can occur in several ways.

One method may be to remove the anodes. Another would be to leave the pipe open at both ends so that seawater can flow in freely. Furthermore, water in the pipes can be circulated to increase the corrosion rate. Another suggestion is to add electrical power. The latest proposal is to install a cathode so that the pipe will be the sacrificial anode.

These are just thoughts without investigating whether this is a practical method that can work well. Without having examined the method, it has been chosen to look more because it is assumed that it is one of the more environmentally friendly and cheaper ideas. Nevertheless, many unknown factors need to be clarified to move forward with the idea.

### 5.2 Corrosion

Initially, it was defined that corrosion is caused by an electrochemical process in which the material in question reacts with the environment. In this report, the surroundings will be seawater.

ISO 8044: 2020 (en) defines as many as 53 different types of corrosion [12]. The type of corrosion discussed further in this report is galvanic corrosion. ISO 8044: 2020 (en) defines this type of corrosion as "Corrosion due to the action of a corrosion cell." A *corrosion cell* is defined as a "short-circuited galvanic cell in a corrosion system." A galvanic cell is thus the combination of different types of electrodes. The corrosion system consists of the metals included in the process and the environment that affects the corrosion process [12].

Based on the definition ISO 8044 2020 (en), three parameters that depend on each other must be met for galvanic corrosion to occur. Two or more different metals must be in electrical contact in an electrolyte. In this case, the electrolyte will be seawater. Furthermore, the pipelines will be of a particular type of metal.

Furthermore, it is considered necessary to include the reaction equations applicable for iron to corrode in seawater.



*Figure 7 Corrosion of iron [13]*

Generally, iron will rust if left out in a humid environment. The reactions thus consist of the iron reacting with the oxygen and the water, which is converted to rust. The actual chemical reaction can be described below and starts with the Reaction equation (5.2.1) [14].

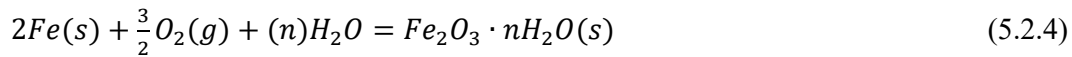
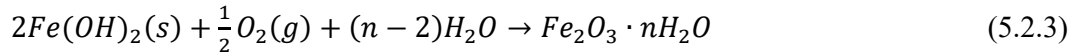


Reaction equation (5.2.1) shows that iron dissolves and forms other ions. Two electrons are released from the iron, which means that the process must continue using the remaining electrons. This is done by using the oxygen in the water.





In Reaction equation (5.2.2), the iron ions and hydroxide ions diffuse towards each other. The fact that the substances diffuse means that they are mixed with another substance. Thus, the iron ions are dispersed into the hydroxide ions. The oxygen diffuses into the water, which will create rust, to create equilibrium in the equation.



Reaction equation (5.2.4) presents the total reaction for the corrosion process. It consists of iron reacting with oxygen in an electrolyte, seawater. This reaction takes several steps, but an important point here is that it is indispensable to have all three substances to create corrosion. In other words, oxygen in the water is just as vital as water.

### 5.2.1 Corrosion of carbon steel in seawater

Metals can corrode both internally and externally in seawater. Det Norske Veritas (DNV) states that internal corrosion will likely occur in oil and gas pipelines [15].

In the book Corrosion and protection by Einar Bardal, corrosion measurements can be performed using three different methods [16]. The first method is to calculate the reduction in the thickness of the material per unit of time. The method is used to calculate how much steel corrodes in millimeters per year. This method is considered a good starting point for further understanding the thesis.

The Equation (5.2.1.1) below applies to the corrosion of carbon steel in seawater.

$$\frac{\Delta s}{\Delta t} = 3268 \frac{i_{corrosion} M}{z \rho} \text{ [mm/year]} \quad (5.2.1.1)$$

$$i_{corrosion} = 1 \cdot 10^{-6} A/cm^2$$

M is the mole mass and z will be 2 according to the Reaction equation.

$$\rho_{carbon\ steel} \approx 7,84 \text{ g/cm}^3$$

Several internal documents in Equinor show that Carbon steel X65 is the most frequently used material in pipelines.

X65 is composed of several materials, and it is considered necessary to find the mole mass of each of the substances to see if the mass will change significantly. The chemical composition of carbon steel X65 is presented in Table 4.

Table 4 Chemical composition of carbon steel

Chemical composition of X65 (Carbon steel)		
Element	Atom mass (g/mol) [17]	Percent in X65 [18]
<b>Iron</b>	55,845	97,591
<b>Carbon</b>	12,011	0,16
<b>Silicon</b>	28,085	0,45
<b>Manganese</b>	54,938	1,65
<b>Phosphorus</b>	30,973	0,020
<b>Sulfur</b>	32,06	0,010
<b>Vanadium</b>	50,941	0,009
<b>Niobe</b>	92,906	0,05
<b>Titan</b>	47,867	0,06

It turns out from the overview in Table 4 that the other mixtures in the iron have very little significance in mole mass. For this reason, it is chosen to use the molar mass for iron further in calculations to calculate how much material is removed each year due to corrosion.

$$\frac{\Delta s}{\Delta t} = 3268 \frac{1 \cdot 10^{-6} A/cm^2 \cdot 55,845 g/mol}{2 \cdot 7,84 g/cm^3} \quad (5.2.1.2)$$

$$\frac{\Delta s}{\Delta t} = \underline{0,0116 \text{ mm/year}} \quad (5.2.1.3)$$

This result agrees well with tables from DNV [19], Corrosion and protection by Einar Bardal [16]. The damage will result in a wall thinning on the inside and places where the coating is damaged.

### 5.3 Materials potential in sea water and material selection

To find materials that can act as a cathode in seawater, there is a need to find a material with a higher potential than carbon steel. The pipe will become the sacrificial anode, while the material with the highest potential will be the new cathode.

Equinor has internally published a presentation on corrosion. An overview of galvanic voltage series in seawater is presented in that document. The most passive and precious metals are presented at the top of Figure 8, while the most corrosive and base metals are presented at the bottom. The figure is included here because it provides a basis for relevant materials [20].

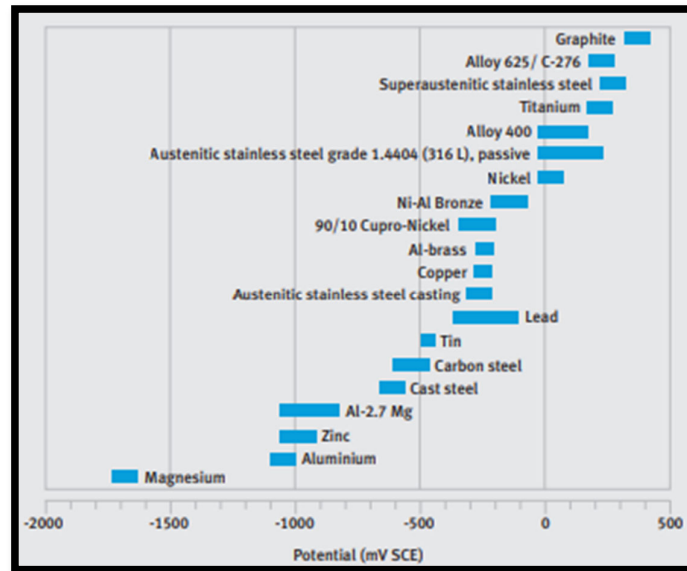


Figure 8 Materials potential in sea water [21]

As mentioned, the materials are listed upwards in order based on their potential in seawater. The red lines in Figure 8 show the material's potential at 40 degrees Celsius, while the blue lines show the potential at 10 degrees Celsius. Magnesium is at the bottom with a low potential of between -1500 to -2000 mV SCE (Saturated Calomel Electrode).

The figure above shows that several material choices can act as a cathode to make the victim anode. All materials that are higher up than the steel can be used. A material that can work well here is AISI 316L, a reasonably common acidproof steel.

Factors that should influence the choice of material here are both availability and cost. If cathodes are to be made for several kilometers with pipes, it will be vital to have large amounts of the material. The need for large amounts of the material comes from the fact that if it is desired that the anode should disappear quickly, the area ratio between cathode and anode must be significant, i.e., large cathode and small anode.

Of the potential materials shown in the figure, there are also considerable differences in cost. After a quick search on the internet, the AISI 316L costs around 400 NOK / Kg. The cost of titanium usually is more than four times as high as AISI 316L per kilogram. The material selection will constitute extreme differences in cost, although titanium would have made the pipeline corrode faster. The material that would have been most efficient to use, based on the figure, is Inconel 625. This material is about twice as expensive as titanium and costs about 3600 NOK / Kg.

#### 5.4 Corrosion time using AISI 316L cathodes

Previously, it has been presented which anodes can be used to cause the pipeline to corrode. This chapter looks at how long it will take to corrode the pipeline using AISI 316L cathodes. Before performing calculations, some of the challenges if such a method is used have been set up.

- The AISI 316L must be in contact with the area to be corroded. It is considered most accessible to mount the cathode on the inside of the pipe.
- The cathode of AISI 316L must be large compared to the amount of steel desired to corrode.
- If the pipeline corrodes away, the cathodes will remain on the seabed. These may then have to be removed afterward.

To say something about how long it will take to corrode the pipeline by installing cathodes, the potential that is achieved when connecting the materials must be known. Furthermore, the exchange current density and the anodic Tafel graph must be known [22].

Faraday's law can calculate how long it will take to corrode the pipe, as presented in Equation (5.4.1) [22]. In the formula it is chosen to use  $w$  for weight,  $i$  as current density,  $t$  for time,  $M$  for molecular weight,  $A$  is anode area,  $z$  for the number of electrons, and  $F_C$  is Faraday's constant. Average values for current density and time can be used to get a result that can indicate how much time is reduced by installing cathodes on the pipeline [22].

The molar mass, the number of electrons, and current density can be obtained from Chapter 5.2.

$$w \text{ [gram]} = \frac{i[A/cm^2] \cdot \Delta t[s] \cdot M \cdot A}{z \cdot F_C} \quad (5.4.1)$$

Another report from 2009 presents an experiment that shows the overview of the corrosion rate in mm/year if the materials in contact are carbon steel and stainless steel, reference to table 5 in Euro Inox's report [21]. As mentioned, the corrosion rate depends on the potential between the materials. Hence, the area difference between the cathode and anode.

In order to find exact values for the change in potential and current density, practical experiments should be made, which can be compared with separate calculations.

Nevertheless, it has been chosen to set up some assumed current densities to illustrate how Faraday's law can be used for calculations. This is illustrated in Table 5.

Table 5 Faraday's law with various current density

Current density		Corrosion rate	
[mA/m <sup>2</sup> ]	[g/sek · m <sup>2</sup> ]	[kg/year · m <sup>2</sup> ]	[mm/year]
<b>0,001</b>	$2,90 \cdot 10^{-7}$	0,01	0,116
<b>0,005</b>	$1,45 \cdot 10^{-6}$	0,05	0,581
<b>0,01</b>	$2,90 \cdot 10^{-6}$	0,09	1,161
<b>0,015</b>	$4,35 \cdot 10^{-6}$	0,14	1,742
<b>0,02</b>	$5,80 \cdot 10^{-6}$	0,18	2,322
<b>1000</b>	0,2901	9150,34	116121

Since no time has been spent finding realistic exchange current densities, numbers between 0,001 mA/m<sup>2</sup> and 1000 mA/m<sup>2</sup> have been entered.

It has not been chosen to look further at how much mass of AISI 316L will be required for the entire pipeline to corrode away due to time constraints and limited knowledge of the subject.

### 5.5 Discussion for reverse cathodic protection

In this chapter of the report, pipeline documentation has been studied. Based on this, it has been decided to discuss the idea relatively early.

The idea is based on reversing the cathode and anode relationship. Emphasis is placed on the coatings and protections of the pipes and the reaction equations and calculations. The idea is innovative and creative, and no similar methods have been found in the existing literature. Furthermore, the idea has been discussed with experts in corrosion and materials science within Equinor.

With the quality of both the coatings and the anodes mounted on the pipes, it is necessary to remove this to make the pipes corrode faster. Once this has been done, according to experts within Equinor, it is reasonable to estimate that the pipe can corrode by 0,01 mm/year. This number agrees well with the calculations made in this report. Furthermore, it is reasonable to assume that the corrosion time is reduced slightly over time after the first corrosion layer has been made. The reduced corrosion time is because the corrosion layer itself will reduce the rate of further corrosion. No time has been spent calculating the amount of mass required of the cathodic material, as this report considers it too demanding. It is assumed that the mass of the cathode must be unrealistically large and that the method is therefore not feasible.

However, it is recommended to install cathodes to speed up the corrosion time. Nevertheless, this has not been discussed in-depth, and there will be opportunities for further research on this topic.

It was mentioned earlier in the chapter that oxygen is necessary for corrosion to occur. In deep water, the amount of oxygen that is supplied is limited. The water will most likely flow in and out of the pipe at the ends. Therefore, there will be most oxygen in this area. If the pipelines are several hundred meters, the oxygen in the middle of the pipe will be used up quickly if there is no water replacement.

There are opportunities to increase the oxygen supply to make the process faster. No other option has been found for such a solution than creating a system where oxygen is supplied. This argument will increase the cost of practicing the method.

Other methods can be used to increase the corrosion rate. As mentioned, corrosion is a current. The process could also be faster if a system were implemented to circulate the water, possibly using voltage. This argument will increase the workload and the costs.

The cost of potential materials is also presented in the report. It turns out that large amounts of material are required to make this method work. The materials required have significant cost differences, but common to all is that they will be expensive in large quantities.

It was chosen early on not to carry out a practical test of the method and instead prioritize presenting several other potential solutions, references made to chapter 3. This was decided as it became a significant challenge to access materials and premises for the experiment, mainly due to the covid-19 situation. In addition, it was decided not to conduct the test as research was done, and others have performed several practical tests for cathodic protection. Therefore, it was concluded early on that a practical test of the method would not be decisive for the report.

## 5.6 Part conclusion

Based on the arguments described in the discussion, the part conclusion will now be presented.

The anodes are welded to the pipe. The anodes could have been installed differently if the method had been suggested before the installation. The concrete could have been avoided in some areas because concrete will not corrode away together with the pipeline itself by using this method. Additionally, concrete would possibly have been possible to avoid in some

places where there would later have been a need for the pipe to corrode away faster. If the method had been effective and the pipe had corroded away, Equinor would still have been responsible for the concrete left on the seabed. This argument is highly emphasized in the conclusion because one of the motivators for looking at the method was to avoid the pipeline is later to the detriment of other sea users.

After calculations, it turns out that the corrosion time will be much slower than first assumed, about 0,01mm / year. If the wall thickness is 24 mm, it will take 2400 years before the entire wall thickness is gone due to corrosion. Two thousand four hundred years is far too long. In addition to the calculated 2400 years, Equinor, as mentioned earlier, still has a concrete pipe left on the seabed. This concrete is considered a significant disadvantage for sea users as the pipeline itself.

Furthermore, no time has been spent calculating total costs and workloads in the report yet. It is also not considered necessary to do so at this stage. This decision was made because it was decided to use the time further to study other methods.

Based on these arguments, it has been decided to move away from this method.

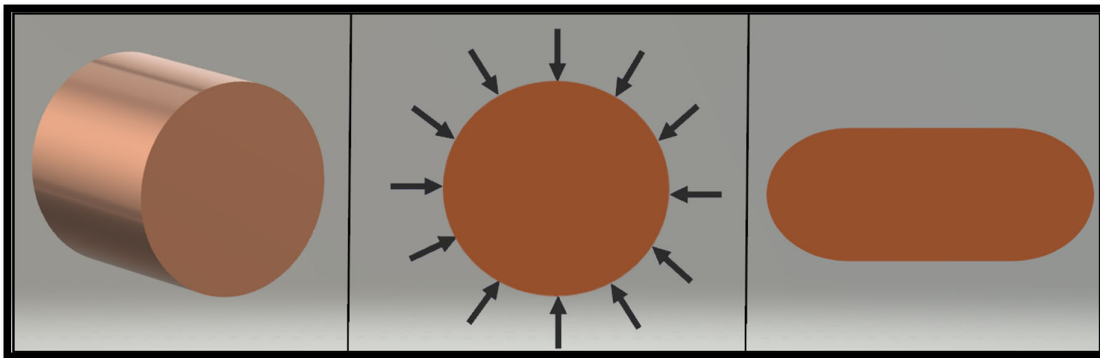
## 6 Second idea, force the pipe to collapse

The principle of making a pipe collapse by itself was proposed in a project assignment last semester in the subject Profile Project. This chapter will be about forcing a pipe to collapse. Furthermore, calculations will be made to see if the idea will also work in practice.

### 6.1 The idea

The idea behind forcing a pipe to collapse is to use the depths of the sea as an advantage. The pipelines are installed at varying sea depths, and the external pressure on the pipe will then vary. The primary motivation for this idea is to avoid or minimize gravel filling and hence the discharge from the ships. In addition, it is considered more manageable for the pipe to be covered by sand due to ocean currents if the pipe is flat.

Earlier in the report, it became known that several of the pipes have a concrete coating on the outside. It can also be beneficial for this task. It is known that concrete cannot withstand large forces in the tensile direction. The idea is that the concrete will break and fall off if enough forces are added for this. Furthermore, the idea is that if the pipe is emptied, a more significant pressure difference is formed on the inside. All pipes have a design pressure which it shall withstand without collapsing. If the pipe receives higher pressure than the design pressure, the pipe will collapse. This idea aims to exceed the differential pressure the pipe can withstand to force the pipe to collapse. If the pipe collapses, this is considered a minor inconvenience to other sea users in retrospect. Figure 9 illustrates what is desirable to happen to the pipe due to external forces. On the left, the pipe is illustrated, while in the middle, the black arrows illustrate that the external forces will act on the entire pipe. The desired result is the far right of the illustration, where the pipe has buckled.



*Figure 9 Illustration of pipe buckling*



No research has been found on whether this theory will work. For that reason, this part of the report will study the principle of forcing the pipe to collapse.

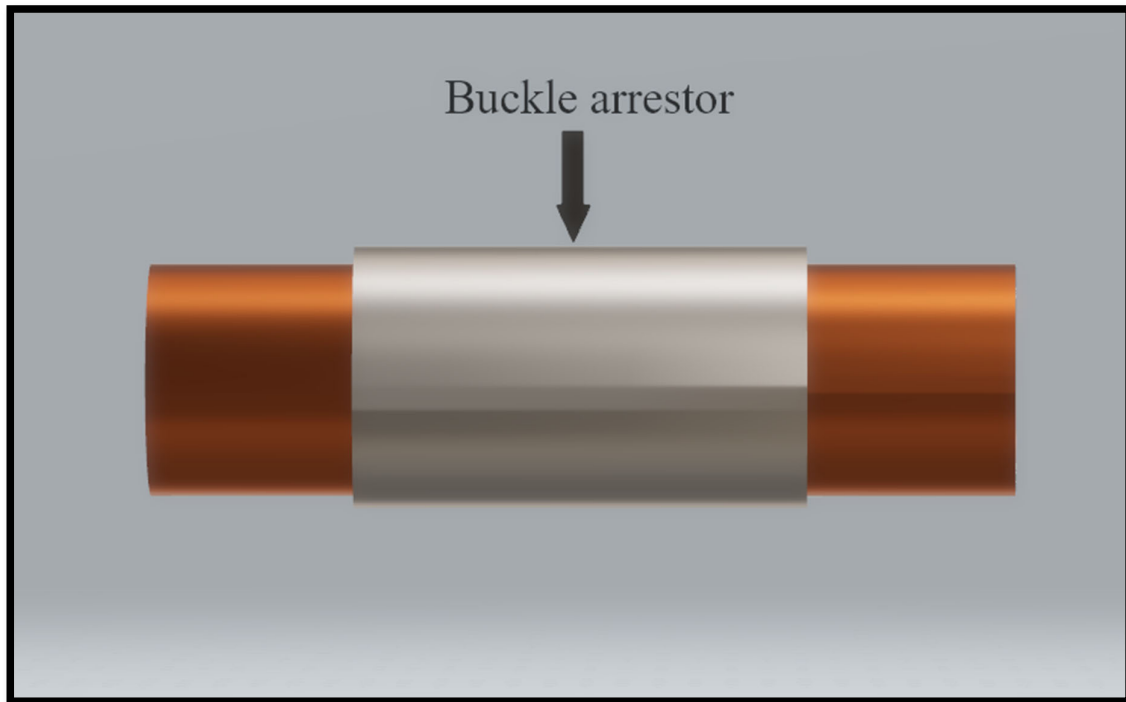
If the pipe does not collapse due to the pressure difference alone, an attempt can be made to weaken the pipe to cause buckling. The impairments can be applied in several ways. To list as many ideas as possible, a table has been made below, Table 6.

*Table 6 Force the pipe to collapse, ideas*

Force the pipe to collapse		
Number	Idea	How
1	Apply loads/forces	Anchor that hits the pipe.
2	Apply loads/forces	Lift the pipe at one of the ends to create bending moment.
3	Weaken the pipe wall	Use a PIG that runs through the pipe to weaken the pipe wall. Here, grinding tools can be used to make the pipe wall thinner, create marks in the inner wall or the like.
4	Additives	Add liquid substances that can accelerate corrosion or etch the material in the pipe.
5	Explosives	Use explosives to destroy the pipeline.
6	Saw	Use a ROV to saw in the outer wall of the pipe.

As in the table, there are many options for weakening the pipe if needed. Some solutions will be less environmentally friendly than others and be more expensive and time-consuming. Therefore, the opportunities considering the environment, the risk of adverse events, and costs are studied.

One of the crucial elements is that many pipes are installed with buckle arrestors. These components make the pipe avoid breaking pipe to the end. A larger pipe is mounted on top of the primary pipe in some areas. The secondary pipe will withstand the forces and terminate a possible propagation buckle. A sketch of this has been made to understand a buckle arrestor, shown below in Figure 10. A propagation buckle will be explained in more detail later in the report.



*Figure 10 Illustration of buckle arrestors*

## 6.2 DNV and API

DNV is known internationally for its standards in several fields. Some are for marine operations, pipelines and risers, material technologies, and more. Before making calculations, it has been chosen to follow the guidelines for calculations that DNV has published.

The pipelines studied in this report have most likely been designed from one of the first versions. The relevant standard was called submarine pipeline systems and was first published in 1976. The latest version was published in August 2021.

The American Petroleum Institute has developed hundreds of standards, and in the summer of 1999, they published their third version of the design, construction, operation, and maintenance of offshore hydrocarbon pipelines.

There are several ways to calculate the collapse pressure or the critical pressure. Both API RP 1111 and DNV OS-F101 describe the collapse situation [23], [24]. It turns out that there are minor differences in the formulas between API and DNV. Nevertheless, it is chosen to make calculations from DNV and API to compare the results. It is important to note that all pipe parameters used in the chapter are taken from Table 6.

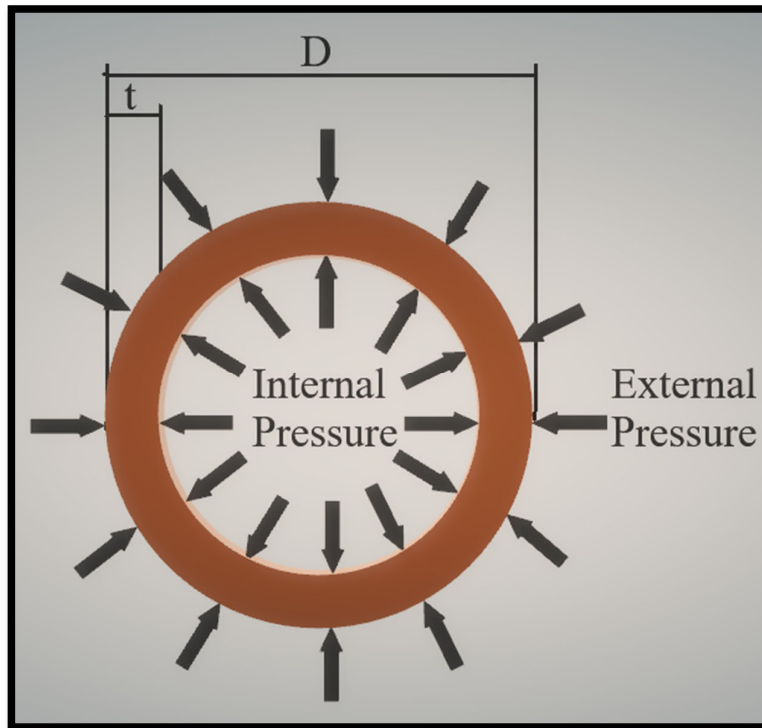
### 6.3 Buckling due to differential pressure

Before starting with calculations, it is necessary to understand what buckling is and how it occurs. Submarine pipelines are used in large parts of the world to transport oil and gas. One of the most critical parameters to consider is the difference between the external pressure on the pipeline and the inner pressure. The external pressure will rise according to the sea depth installed at the pipeline. The external pressure is called hydrostatic pressure, which acts from the seawater on the pipeline. The hydrostatic pressure is due to the weight of the seawater and gravity. Hydrostatic pressure must be considered when designing the pipe. If the critical pressure of the pipe is lower than the external pressure, it may cause the pipe to change shape [25]. The pipe is compressed due to the differential pressure, and in the worst case, it can lead to buckling. The main reason the pipe breaks is thus the pressure difference on the inside and outside of the pipe.

### 6.4 Collapse pressure

As a starting point for calculations, it has been chosen to calculate the collapse pressure. The collapse pressure will provide an answer to how high external pressure is needed to get to make the pipeline collapse. The collapse of the pipe will only occur if the differential pressure around the pipe exceeds the strength of the pipe [26]. Collapse pressure is the pressure required to buckle a pipeline. There are several types within the theme of buckling, including local buckling, propagation buckling, and upheaval buckling. Upheaval buckling often comes from axial forces due to, for example, temperature or pressure during operation.

To give a more detailed description of which factors will be necessary for collapse and how those forces act, an illustration has been made in Figure 11. "D" represents the outside diameter of the pipe, while "t" represents the thickness of the pipe. The arrows on the inside and outside of the pipe illustrate internal and external pressure, respectively.



*Figure 11 Illustration of internal & external pressure, diameter, and thickness of a pipeline*

When the pipe is exposed to pressure, the pipe will also be exposed to stress. This tension is called hoop stress and tension in the axial direction. The axial stresses will only affect the ends due to the length of the pipe. For that reason, axial stress is neglected in this report. For that reason, it can further be assumed that buckling occurs when  $P = P_c$  [1]. Because no information has been found that a concrete cover is required to install, and because it is unknown whether all pipelines have it, it is assumed that if there is concrete around the pipe, the concrete does not have an impact on the collapse.

The bending moment is neglected in the calculations. This is because the idea is that the pipe is not attached to either end. If it turns out that the pipe will not collapse based on the differential pressure, it may be an idea to cut the pipe at one end while it is fixed at the other end or to apply an extra force. In this way, a bending moment may occur.

#### 6.4.1 Calculation of collapse pressure, API

The collapse pressure is calculated based on elastic, plastic, and total collapse pressure. Equation (6.2.1.1) to (6.2.1.3) are taken from API's recommended practice, published in 1999 [23].

$$P_{el} = \frac{2E}{1-\nu^2} \left(\frac{t}{D}\right)^3 = \frac{2 \cdot 210 \text{ GPa}}{1-0,3^2} \left(\frac{17,5 \text{ mm}}{508 \text{ mm}}\right)^3 = \underline{18,868 \text{ MPa}} \quad (6.4.1.1)$$

$$P_{pl} = 2\sigma_y \frac{t}{D} = 2 \cdot 413 \text{ MPa} \cdot \frac{17,5 \text{ mm}}{508 \text{ mm}} = \underline{28,454 \text{ MPa}} \quad (6.4.1.2)$$

$$P_c = \frac{P_{pl} P_{el}}{\sqrt{P_{el}^2 + P_{pl}^2}} = \frac{(28,454 \cdot 18,868) \text{ MPa}}{\sqrt{(18,868)^2 + (28,454)^2 \text{ MPa}}} = \underline{15,724 \text{ MPa}} \quad (6.4.1.3)$$

$$P_e = h\rho g = 310 \text{ m} \cdot 1029 \text{ kg/m}^3 \cdot 9,82 \text{ m/s}^2 = \underline{3,129 \text{ MPa}} \quad (6.4.1.4)$$

As shown in the formulas above, the relationship between the wall pipe's thickness and the diameter is significant. These are also the most important parameters when designing the pipes. The thickness and diameter ratio must be correct so that the pipe does not collapse even before being produced.

Although the calculations above are crucial for the installation and the pipe's service, the formulas have been simplified. The calculations above are based on formulas for perfect round pipes. Out of roundness in the pipe can occur for several reasons. This can occur in connection with the fabrication of the pipe, but it can also occur later in connection with installation, falling objects, corrosion, and more. Such information is not easy to know without having access to inspection reports or similar documents. Therefore, it is assumed in this thesis that the pipe's only ovality comes from the pipe's fabrication. Calculations of the ovality can be of great importance for the load-bearing capacity of the pipe. Timoshenko has therefore made an expression where the calculations take the ovality into account. The safety factor  $f_0$  is 0,7 for seamless or electric resistance welded (ERW) pipes [23].

$P_i$  is used for the internal pressure.

According to DNV, the pipe's collapse pressure must be higher than the net external pressure. Since a collapse is wanted in this report, the collapse pressure must be less than the net external pressure for the pipe to collapse [23].

$$(P_e - P_i) \geq f_0 \cdot P_c \quad (6.4.1.5)$$

$$3,129 \text{ MPa} \leq 11,006 \text{ MPa} \quad (6.4.1.6)$$

Based on the calculation above, it is shown that the pipe will not collapse if the pipe is the same size over its entire length. By that means, there is no impact from corrosion or other issues that might reduce the thickness of the pipe. In the calculations, it is assumed that the water has been pumped out entirely and that the internal pressure will therefore be equal to

zero atmospheric pressure. This is a simplification, but it is considered a necessary simplification to avoid using advanced analysis programs due to a lack of additional information.

Although the calculations by hand show that the pipe is sufficiently designed and will therefore not collapse, it has been chosen to look at the case in an analysis program to figure out what is required to force the pipe to collapse.

The simplifications made, several factors have been neglected, including the change in wall thickness or other weakening during the lifetime. These factors can impact whether the method will work or not.

The propagation pressure that is now calculated is the minimum pressure required to maintain the propagation in the line. There are several formulas to calculate the propagation pressure. There is, among other things, a 2D approximation for propagation buckling, but there is also an extension of this formula that should be more accurate. As the API standard was used earlier in this chapter, the report continues using these formulas in Equation (6.4.1.7) and (6.4.1.8) [23].

$$P_{Pr} = 24\sigma_y \left(\frac{t}{D}\right)^{2,4} \quad (6.4.1.7)$$

$$P_{Pr} = 24 \cdot 413\text{MPa} \left(\frac{17,5\text{mm}}{508\text{mm}}\right)^{2,4} = \underline{3,058 \text{ MPa}} \quad (6.4.1.8)$$

This pressure is much lower than the collapse pressure calculated earlier in the report. The pressure difference agrees well with the theory, which says that lower pressure is required to uphold the deformation once it has occurred.

The results from the calculations in this chapter are presented in Table 7.

Table 7 Results from calculations with API

Results from calculations API		
<b>Plastic collapse</b>	$P_{pl}$	28,454 MPa
<b>Elastic collapse</b>	$P_{el}$	18,868 MPa
<b>Collapse pressure</b>	$P_c$	15,724 MPa
<b>External pressure</b>	$P_e$	3,129 Mpa
<b>Pressure difference</b>	$P_e - P_i$	3,129Mpa
<b>Propagation pressure</b>	$P_{Pr}$	3,058 MPa

What is positive from the table here is that it turns out that the differential pressure between internal and external pressure is greater than the propagation pressure. That is, it will be possible to create propagation collapse.

#### 6.4.2 Calculation collapse pressure, DNV

In this chapter, the report will look at calculations of critical pressure and propagation pressure using DNV's latest version of the standard "Submarine pipeline systems" [27].

DNV has made minor changes since the previous version of the standard. An analytical formula must calculate the collapse pressure, as shown below in Equation (6.4.2.1).

$$[P_c(t) - P_{el}(t)][P_c(t)^2 - P_{pl}(t)^2] = P_c(t) \cdot P_{el}(t) \cdot P_{pl}(t) \cdot O_0 \cdot D/t \quad (6.4.2.1)$$

Only a few parameters have not been looked at in the formula above. The only parameter that has not been addressed earlier in the report is  $O_0$ , which considers the pipe's ovality.

The tolerance for the wall thickness is + 5% to + 8%. In this case, + 5% is used as the maximum diameter. This tolerance equates to 25,40mm over 508mm. The minimum diameter will be 508mm [28].

The calculations assume that  $\alpha_{fab}$  is for a seamless pipeline, and the value is then 0,93.

$$P_{el} = \frac{2E\left(\frac{t}{D}\right)^3}{1-\nu^2} = P_{el} = \frac{2(210MPa)\left(\frac{17,5mm}{508}\right)^3}{1-0,3^2} = \underline{18,868 MPa} \quad (6.4.2.2)$$

$$P_{pl} = \sigma_y \cdot \alpha_{fab} \cdot \frac{2 \cdot t}{D} = 413MPa \cdot 0,93 \cdot \frac{2 \cdot 17,5mm}{508mm} = \underline{26,462 MPa} \quad (6.4.2.3)$$

$$O_0 = \frac{D_{max} - D_{min}}{D} = \frac{(508+25,40)mm - 508mm}{508mm} = \underline{0,05 mm} \quad (6.4.2.4)$$

$$P_{pr} = 35 \cdot \sigma_y \cdot \alpha_{fab} \cdot \left(\frac{t}{D}\right)^{2,5} = 35 \cdot 413MPa \cdot 0,93 \cdot \left(\frac{17,5mm}{508mm}\right)^{2,5} = \underline{2,960 MPa} \quad (6.4.2.5)$$

The analytical solution to equation 6.4.2.1 is shown in Equation (6.4.2.6) to (6.4.2.13) below.

$$P_c = y - \frac{1}{3}b \quad (6.4.2.6)$$

$$b = -P_{el} \quad (6.4.2.7)$$

$$c = -\left(P_{pl}^2 + P_{pl} \cdot P_{el} \cdot O_0 \cdot \frac{D}{t}\right) \quad (6.4.2.8)$$

$$d = P_{el} \cdot P_{pl}^2 \quad (6.4.2.9)$$

$$u = \frac{1}{3}\left(-\frac{1}{3}b^2 + c\right) \quad (6.4.2.10)$$

$$v = \frac{1}{2}\left(\frac{2}{27}b^3 - \frac{1}{3}bc + d\right) \quad (6.4.2.11)$$

$$\varphi = \cos^{-1} \left( \frac{-v}{\sqrt{-u^3}} \right) \quad (6.4.2.12)$$

$$y = -2\sqrt{-u} \cos \left( \frac{\varphi}{3} + \frac{60\pi}{180} \right) \quad (6.4.2.13)$$

To calculate Equation (6.4.2.1), an Excel sheet has been made. This sheet calculates the collapse pressure based on ovality and the ratio between the diameter of the pipe and the wall thickness. Several parameters have been inserted in the Excel sheet; these are described in Table 8.

Table 8 Input to formula from DNV for collapse pressure

		Range		Step
		Low	High	
<b>Diameter to Thickness ratio</b>	D/t	27	30	0,1
<b>Ovality</b>	O [%]	0,05	0,1	0,1
<b>Fabrication factor</b>	$\alpha_{fab}$	0,93		
<b>Yield stress</b>	$f_y$	413 MPa		
<b>Elastic modulus</b>	E	201000 MPa		207000
<b>Poisson's ratio</b>	v	0,3		

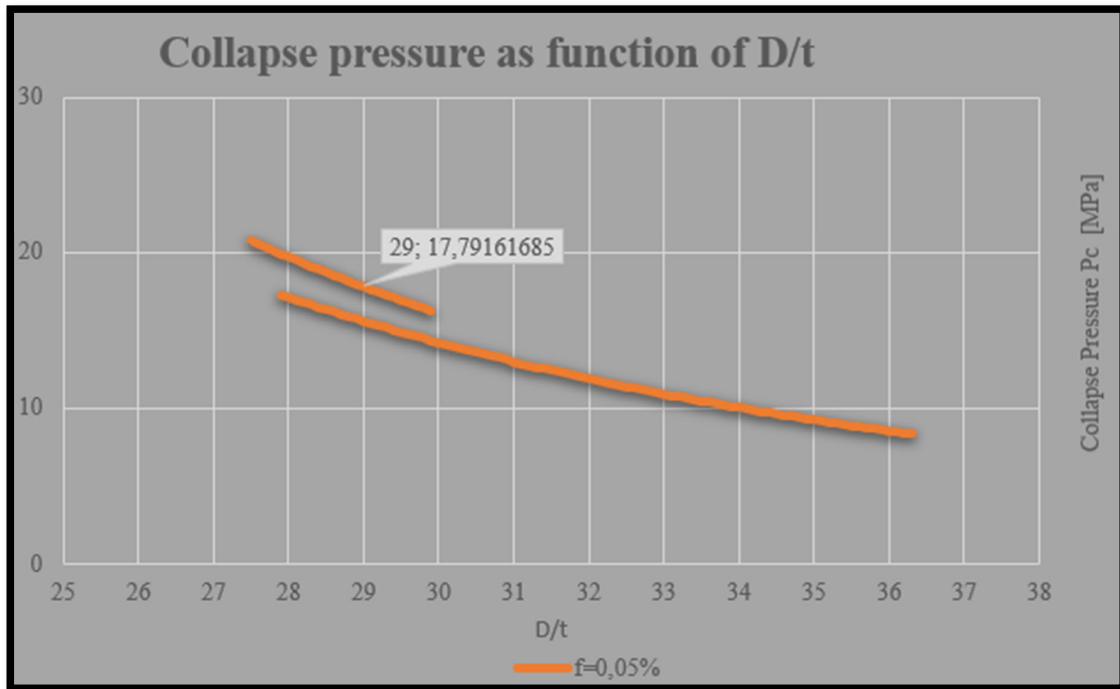


Figure 12 Collapse pressure as function of D/t

Figure 12 shows how high the collapse pressure will be because the ovality is 0,5%, and the ratio between the diameter and the pipe thickness is 29. The collapse pressure will be about 18 MPa.



The results from the calculations in this chapter are presented in Table 9.

Table 9 Results from DNV calculations

Results from calculations, DNV		
<b>Plastic collapse</b>	$P_{pl}$	26,462 MPa
<b>Elastic collapse</b>	$P_{el}$	18,868 MPa
<b>Collapse pressure</b>	$P_c$	17,791 MPa
<b>External pressure</b>	$P_e$	3,129 MPa
<b>Pressure difference</b>	$P_e - P_i$	3,129 MPa
<b>Propagation pressure</b>	$P_{Pr}$	2,960 MPa

In the chapter where the API calculation was presented, it was also said that the differential pressure between internal and external pressure is greater than the propagation pressure. It turns out that when using DNV's standard, this case is the same. It is reasonable to assume that the wall thickness has decreased during service, and the propagation pressure will lower. Additionally, the wall thickness should be recalculated before implementing such a scenario.

#### 6.4.3 Comparing DNV and API results

In the report, calculations have been made of critical pressures from DNVs and API guidelines. This chapter will compare the results from the calculations before the scenario is modeled in the analysis program ANSYS.

Table 10 Comparison between API and DNV calculations

Parameter	Symbol	Results from calculations API	Results from calculations DNV	Difference between API and DNV
<b>Plastic collapse</b>	$P_{pl}$	28,454 MPa	26,462 MPa	-7,000%
<b>Elastic collapse</b>	$P_{el}$	18,868 MPa	18,868 MPa	-
<b>Collapse pressure</b>	$P_c$	15,724 MPa	17,792 MPa	13,370%
<b>External pressure</b>	$P_e$	3,129 MPa	3,129 MPa	-
<b>Pressure difference</b>	$P_e - P_i$	3,129 MPa	3,129 MPa	-
<b>Propagation pressure</b>	$P_{Pr}$	3,058 MPa	2,960 MPa	-3,204%

In Table 10, the differences in percentage between the two standards used in connection with the calculations are shown. The most significant difference is the results from the calculations

of the collapse pressure. API only includes plastic and elastic pressure in the calculations of the collapse pressure, while DNV has, in its latest version of the standard, including the ovality of the pipe as a parameter in the formula for collapse pressure. The ovality may be one of the reasons for the significant difference of over 7%.

Furthermore, it turns out that there is about a 3% difference in the results of propagation pressure. Both standards consider the yield strength and the ratio between the wall thickness and diameter of the pipe. DNV, on the other hand, includes a fabrication factor that says something about how the pipe is manufactured. This is not included in the API standard, and the difference in the results comes partly from here. The constants multiplied by DNV, and API are 24 and 35, respectively.

### 6.5 Propagation buckling because of a dent

In the previous chapter, calculations were made to see if the difference between external and internal pressure could cause the pipe to collapse. From calculations, this pressure difference will not be big enough. For this reason, it has been chosen to study whether it may be possible to apply a force at a point of the pipe to weaken the pipe. Hence, the purpose is to start the collapse of the pipeline. This collapse method will, in theory, work if there are no physical elements that stop the collapse. Noteworthy, the collapse will end where the external pressure is too small. This will thus be a challenge where the sea depth is not deep enough. This theory exists and is called propagation buckling. Propagation buckling is driven by external pressure and a local weakening in the pipeline. If both factors occur, the collapse of the pipe can occur at high speed and can flatten the pipe.

There are several stages of propagation buckling. The steps are illustrated in Figure 13.

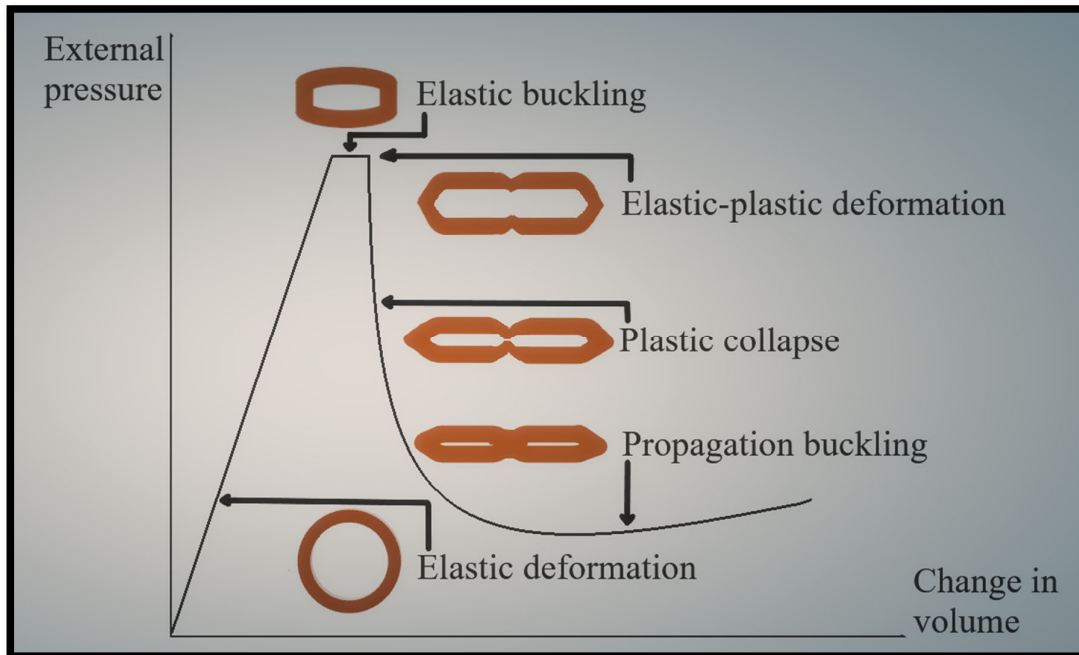
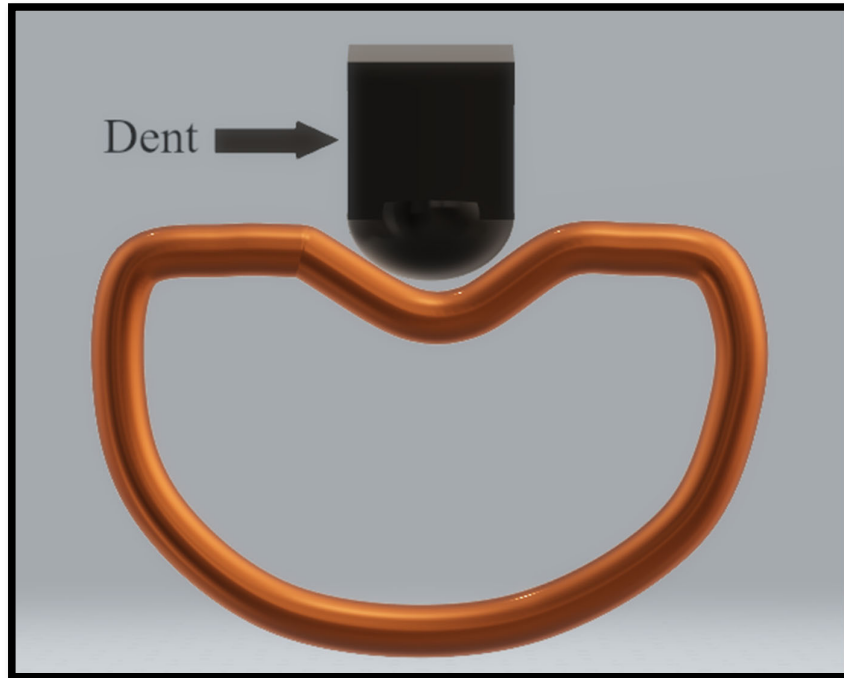


Figure 13 Propagation buckle [29]

As illustrated, the first load on the pipe is elastic. As long as the pipe is in the elastic zone, the pipe can return to its original form because the material has no changes in its structure in this phase. After the elastic phase, the pipe will move into a plastic collapse where it will be impossible to make the pipe return to its original shape. Due to the volume change, it will require less external pressure to make the pipe collapse. If the pressure after the plastic collapse is maintained, the pipe will flatten out. Further, this is illustrated as propagation buckling.

An extra force is needed locally on the pipe to cause propagation pressure. The force that will cause the pipe to collapse will be the local force and will thus cause a local buckling. Local buckling is necessary to create a propagation buckling further in the line. DNV describes local buckling as a significant change in the cross-section of the pipe [24].

The pressure that must be maintained to have a permanent deformation was already calculated earlier in the report. The plastic pressure for the selected pipe will be about 28 MPa, which corresponds to almost 2855 tons per square meter. In other words, DNV's definition of local buckling is the same as plastic deformation of the pipe. The dent in the pipe is illustrated in Figure 14.



*Figure 14 Dent illustration*

In DNVGL-RP-F107 [30], damage to the pipe due to an external force is divided into three classes. The first is minor damage and will not cause any repairing requirements. Furthermore, moderate damages must be repaired, but the damage will not break the pipe. The last class is significant damage, where the pipe section exposed to the forces must be removed before a new pipe section is inserted. In the last class, there are also three subclasses [30].

DNV further writes that the wall thickness and the protective layer locally where the object hits the pipe are essential. Furthermore, the type of object will also be of great importance. If, for example, a container hits the pipe, it will absorb a lot of energy. On the other hand, much higher energy can be supplied to the pipe if it is a different object. Due to the uncertainties associated with this, using only Equation (6.5.1) for estimates is recommended. All classes are described in Table 11.

Table 11 Damage classification [30]

Damage classification	
<b>D1</b>	Minor damage: No repair required and no release of hydrocarbons. Up to 5% deep dent of outer diameter.
<b>D2</b>	Moderate damage: Repair required, no release of hydrocarbons. Above 5% deep dent of outer diameter.
<b>D3</b>	Major damage: Repair required, lead to release of hydrocarbons. May lead to replacing the pipe spool.
<b>R0</b>	No release
<b>R1</b>	Small release
<b>R2</b>	Major release

To calculate the absorbed energy for the pipe, the formula from DNV-GL below is used in Equation (6.5.1) and (6.5.2) [30].

$$E = 16 \cdot \left(\frac{2\pi}{9}\right)^{\frac{1}{2}} \cdot m_p \cdot \left(\frac{D}{t}\right)^{\frac{1}{2}} \cdot D \cdot \left(\frac{\delta}{D}\right)^{\frac{3}{2}} \quad (6.5.1)$$

$$m_p = \frac{1}{4} \sigma_y t^2 \quad (6.5.2)$$

$$E = 13,37 \cdot 0,25 \cdot 413 \cdot \frac{10^6 N}{m^2} \cdot (0,0175m)^2 \cdot \left(\frac{0,508m}{0,0175m}\right)^{\frac{1}{2}} \cdot 0,508m \cdot \left(\frac{0,03m}{0,508m}\right)^{\frac{3}{2}} \\ = \underline{12,96 \text{ kJ}} \quad (6.5.3)$$

For other scenarios, a table has been made below, Table 12. Above it shows that it will require around 13kJ to make a dent of 5% of the diameter. In addition, a calculation of the force in units of kilograms Newton is attached. This force is calculated by dividing the impact energy on the section, i.e., the dent depth.

Table 12 Scenarios for absorbed energy

Dent/diameter [%]	Dent depth [m]	Impact energy [kJ]	Force [kN]
<b>5</b>	0,03	12,93	509,15
<b>10</b>	0,05	36,58	720,04
<b>15</b>	0,08	67,20	881,87
<b>20</b>	0,10	103,46	1018,29
<b>25</b>	0,13	144,59	1138,49
<b>30</b>	0,15	190,06	1247,15

The calculations of absorbed energy calculated above will not answer whether the dent in the pipe will cause the pipe to be subjected to propagation collapse. On the other hand, the calculations will indicate how much energy is required. It has been chosen to include this in the report because it shows from several studies that even if the external pressure is low, it can reduce the capacity to absorb the energy supplied to the pipe [31].

ANSYS will be used to analyze whether the pipe propagates or not. ANSYS is used to get a more visual and hopefully more accurate scenario presentation.

## 6.6 ANSYS

ANSYS stands for analysis of systems [32]. Finite element analysis is made and accounts for both material and geometric nonlinearities for the analysis. The program is thus a finite-element modeling program. The program can be used in several contexts, including analysis of mechanical issues such as fluid mechanics, heat transfer, etc.

In connection with this master's thesis, ANSYS is mainly used to calculate how much external force is required to collapse the pipeline. Simplifications and procedures are presented before a review of the results from the analysis is presented. Finally, the comparison will be presented and discussed.

Simplifications have been made to the analysis program ANSYS as follows:

- The first assumption is that the pipeline is installed at the same depth, 310 meters sea depth. This simplification means that the external pressure from the seawater will be the same along the entire pipe.
- It is further assumed that it is possible to expel the water in the pipeline and close it so that the internal pressure of the pipe will be near 0 MPa. These are the same assumptions made in calculations.
- For elements in ANSYS, shell elements are used. When using shell elements in the program, it is essential to note that the radius at the center of the surface is used. This method is further described in the chapter as mid-surface, i.e., outer diameter minus the wall thickness ( $0,508 \text{ m} - 0,0175 \text{ m} = 0,4905 \text{ m}$ )
- Furthermore, the temperature of the water has not been considered. The temperature used in the analysis is 22 degrees Celsius, but it has been decided that this will not make much difference to the material properties. The temperature will influence the material in a way that is called de-rating. Since the average temperature for seawater

is about 4 degrees Celsius, and DNV-ST-F101 states that temperatures should not be considered unless it is above 50 degrees Celsius, the temperature is not considered in this report [27].

Several simplifications and assumptions are made during the analysis and are presented further in the chapter.

The first thing that is inserted into the program is the suitable material. The material used in the analysis is carbon steel X65.

Table 13 provides an overview of the material properties implemented in the FE program to make the analysis as accurate as possible for the selected material, X65.

Table 13 Material Data implemented in ANSYS

Material Data implemented in ANSYS	
<b>Density</b>	7850 kg/m <sup>3</sup>
<b>Young's Modulus</b>	2,0 · 10 <sup>11</sup> Pa
<b>Poisson's Ratio</b>	0,3
<b>Bulk Modulus</b>	1,6667 · 10 <sup>11</sup> Pa
<b>Shear Modulus</b>	7,6923 · 10 <sup>10</sup> Pa
<b>Yield Strength</b>	4,13 · 10 <sup>8</sup> Pa
<b>Tangent Modulus</b>	1,10 · 10 <sup>10</sup> Pa
<b>Maximum Equivalent Plastic Strain (EPS)</b>	0,15

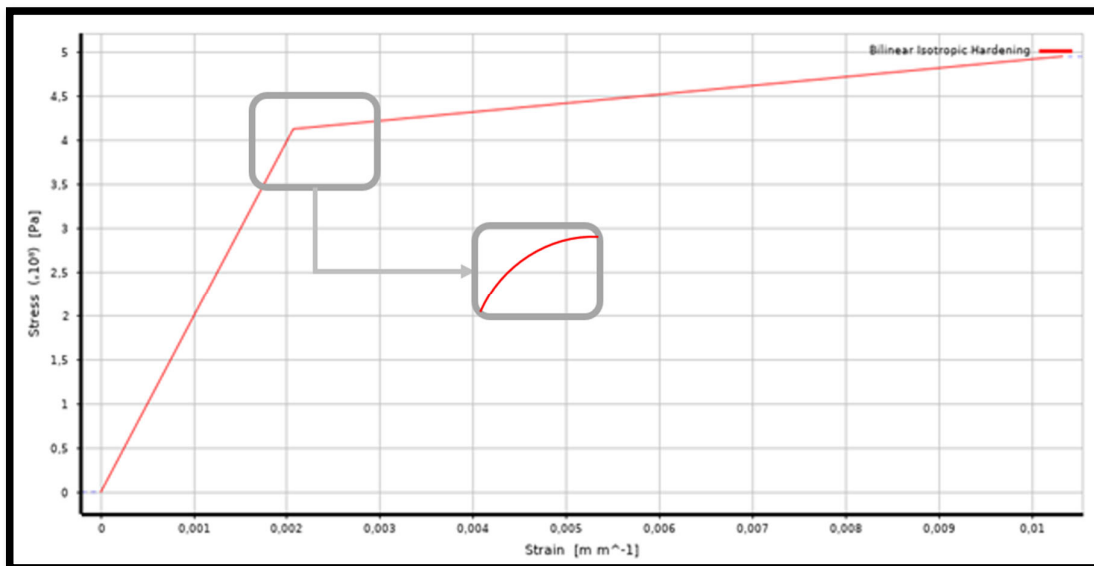


Figure 15 Bilinear Isotropic Hardening

An attempt has been made to illustrate the graph in an ideal case in Figure 15. Due to limited material information, it has been chosen to set up the graph in a simplified way. The sharp corner may impact the results, but it is assumed that this impact is negligible and suitable for the purpose here.

The same pipe size is used in chapter 5.2: the outer diameter is 508 mm, and the mid-diameter is 490,5 mm. A pipe length of 5000 mm is selected to shorten the analysis time. These parameters are presented in Figure 16. This length is relatively short, and if "flip-flop mode" will occur as discussed in [33], it is unlikely that this will be included in the short pipe length.

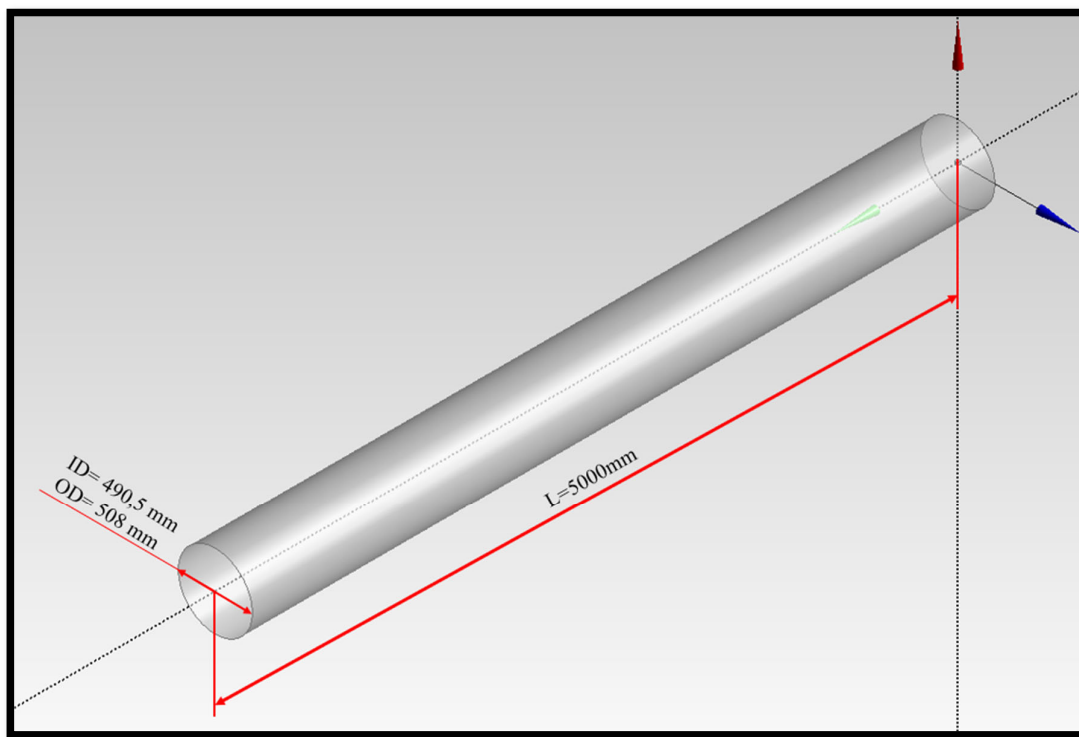


Figure 16 Pipeline parameters

#### 6.6.1.1 Collapse pressure

A simple analysis is first performed in ANSYS to check whether the calculated collapse pressure corresponds to earlier calculations according to DNV and API.

The pressure is inserted as turbulence so that it increases with time. The pressure will start at 0 MPa and rise steadily up to 30 MPa. 30 MPa is far higher than the pressure in calculations to ensure that the pipe will collapse. Other than the applied pressure, a gravity of  $9,81 \text{ m/s}^2$  is



added, and fixed support attaches to nodes at the bottom of the pipe. The parameters are presented in Figure 17.

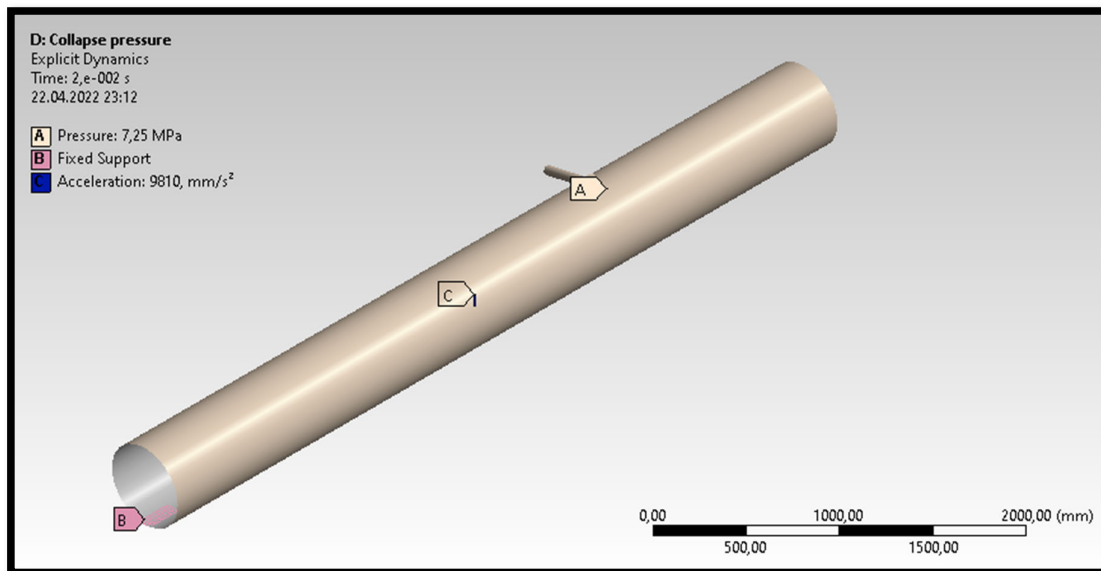


Figure 17 Set up for analyzing the collapse pressure

The size of the mesh is 25mm, as illustrated in Figure 18.

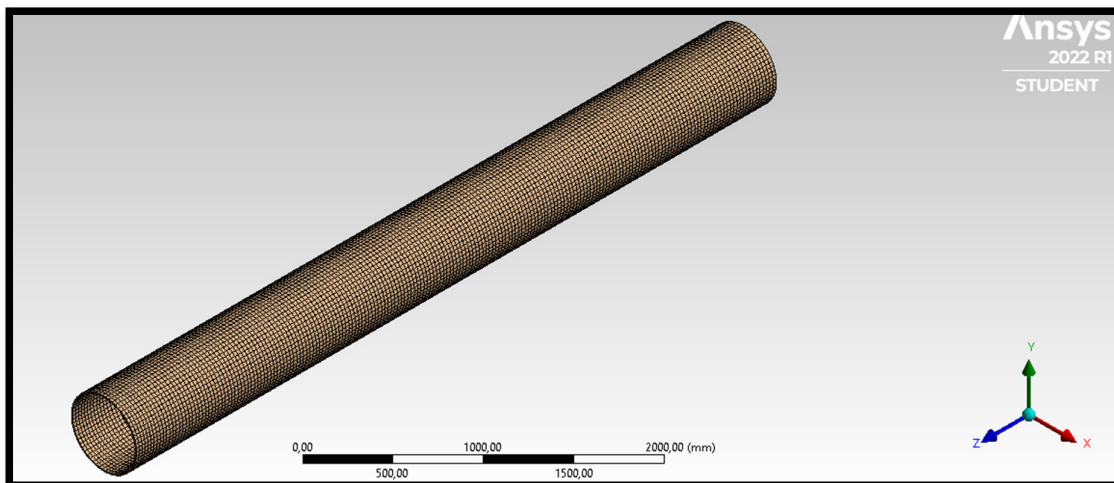
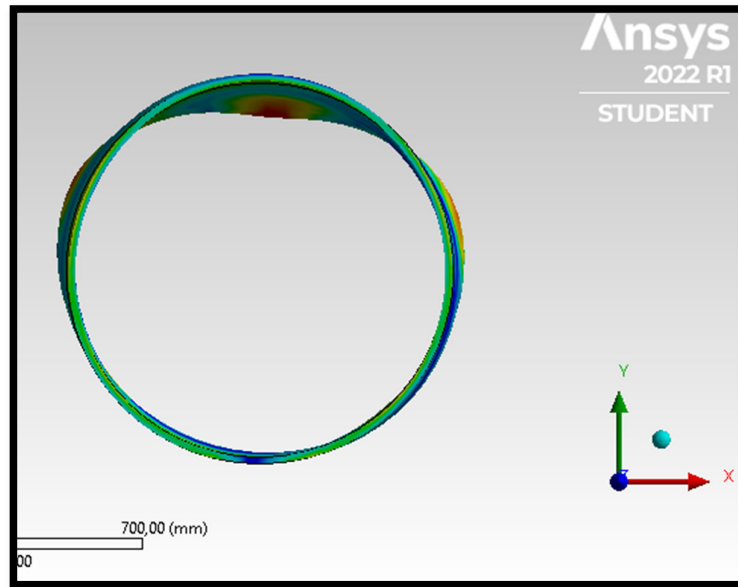


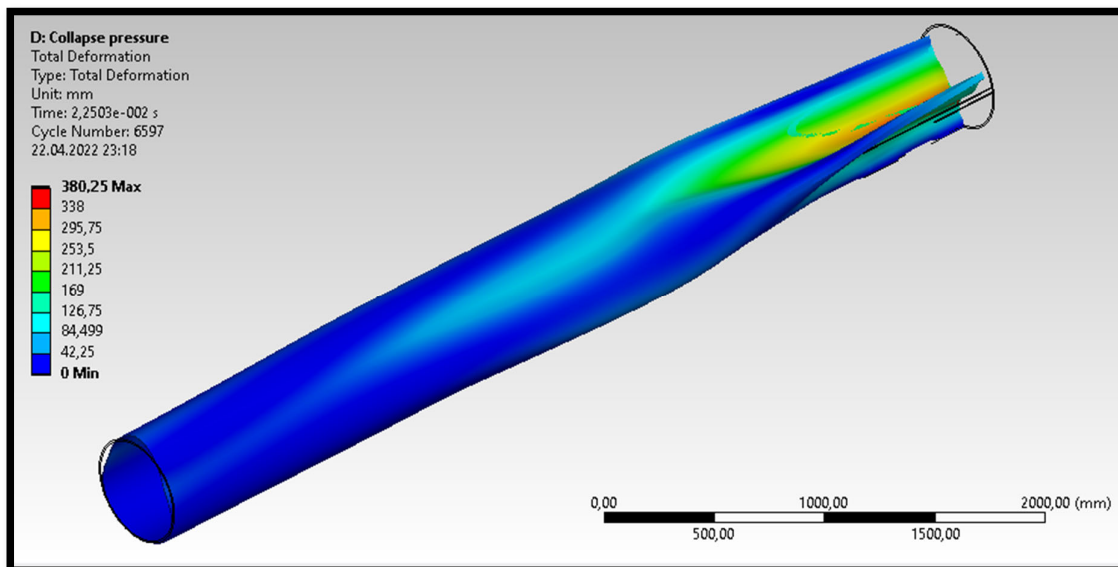
Figure 18 Mesh size

Already at 7 MPa, the pipe starts to collapse. The start of the collapse is shown in Figure 19.



*Figure 19 Start of the pipe collapse*

At 16 MPa, the pipe collapses, and the collapse propagates further under the same pressure. This is shown in Figure 20.



*Figure 20 Pipe collapse*

This analysis is not innovative, and calculations for the collapse have already been performed. It is nevertheless included to compare the calculated collapse pressure and the collapse pressure calculated in the FE program. Any discrepancies are presented later in the report.

### 6.6.1.2 Collapse due to a dent

In this part of the report, the analysis of collapse using a dent will be presented. The new experiment is illustrated below and can be compared with the layout in an article on nonlinear finite element analysis for collapse behavior in dented pipelines published in 2014 [34]. Reference [34] has used different shapes on the dent that hits the pipeline. Due to time limitations, only one shape of the dent has been used in this report: a flat plate. The desired result is to flatten the pipe at the top and bottom before further collapses.

The same forces mentioned earlier are implemented, including external pressure of 3MPa. The pipe is pressurized with constant pressure. The load is applied through the indenter until collapse. As illustrated in Figure 21, Force A is the prescribed denting displacement. For the first attempt, it is inserted that the plate is to be pushed down 50mm into the pipe. This displacement corresponds to approximately 10% of the outer diameter of the pipe. The second remote displacement is added to support the plate that illustrates the seabed. All parameters are presented in Figure 21.

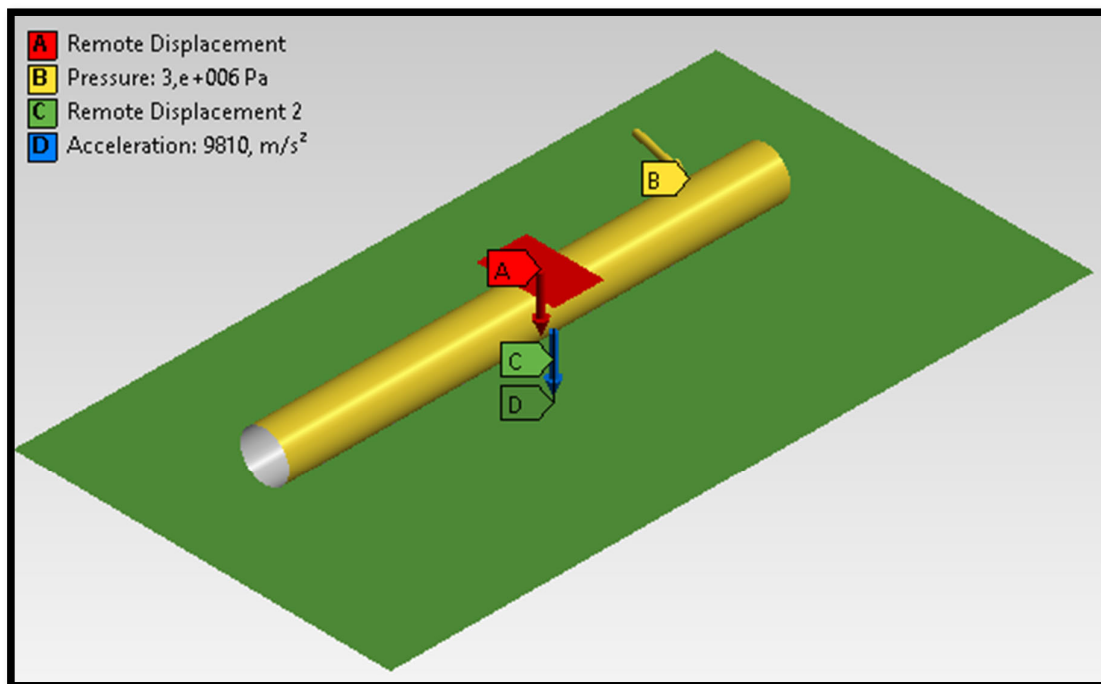
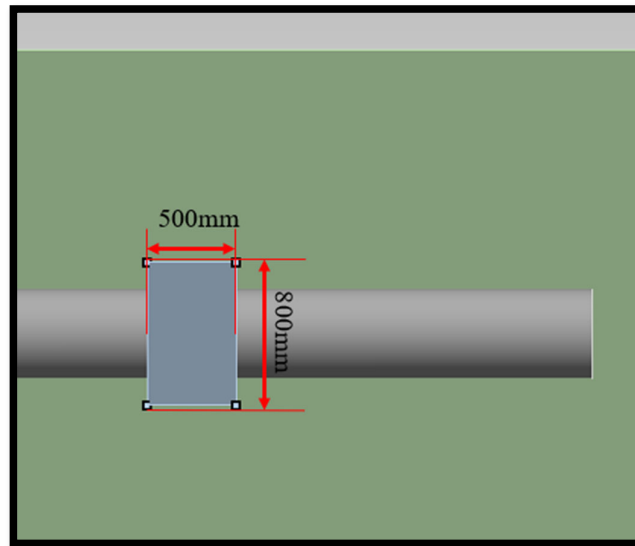
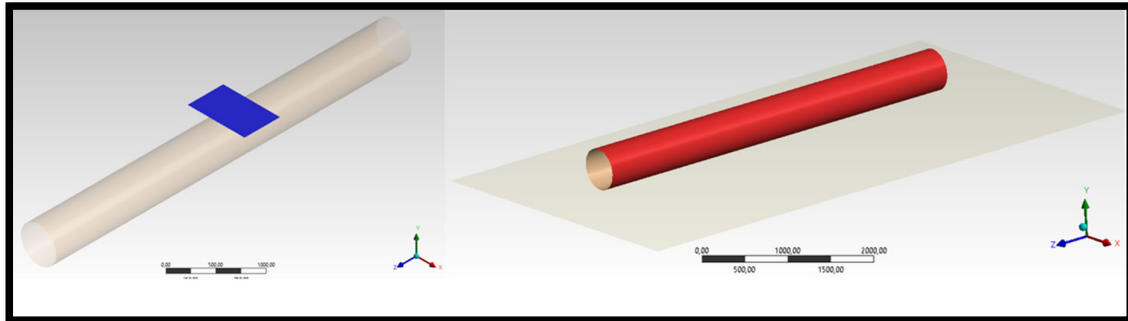


Figure 21 Set up for dent analysis



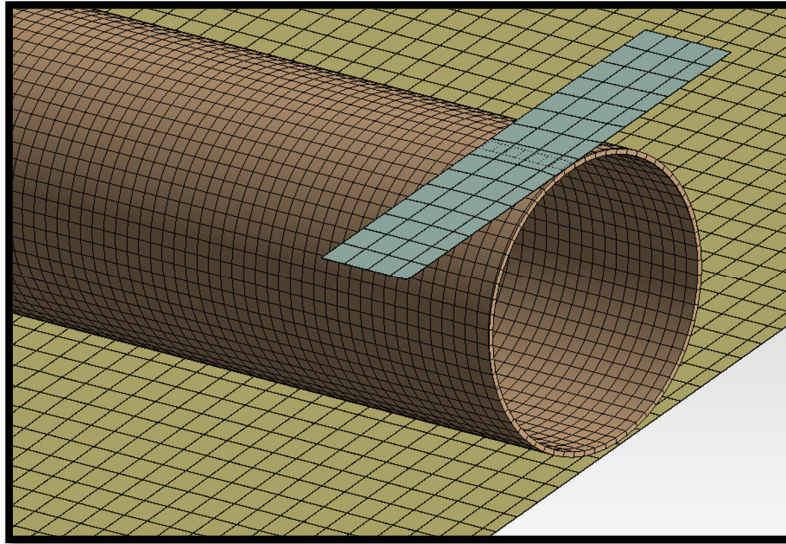
*Figure 22 Rigid plate, size*

The size of the plate on top can be essential and is, therefore, shown in Figure 22. The width selected is 500mm, but it is assumed that the results will change if the plate is broader or shorter. The size can be further analyzed if this method is to be used. As the size of the plate used as a seabed is insignificant, no measurements are taken for this.



*Figure 23 Connections between the parts*

The frictionless contact has been used to interface the pipe and the rigid top plate (indenter). In addition, a bonded connection is inserted between the plate, which illustrates the seabed and the pipe. These two connections are illustrated in Figure 23.



*Figure 24 Mesh size*

The sizes of the mesh vary for the different parts. It is chosen to use a 25mm size for the pipe itself, while for the two plates, a size of 50mm is used. The mesh is presented in Figure 24.

The first attempts at the pipeline collapse are attached in APPENDIX A.

It is chosen to make further analyzes of explicit dynamics in ANSYS. Explicit dynamics are mainly used because this will provide an opportunity to see a physical change that takes place in the short time period for nonlinear forces. In other words, it will be possible to see whether the collapse propagates or not.

For this model, a new geometry is created. The pipeline will have the same parameters, but the mid-surface is used to create the geometry, which will give acceptance for finite membrane stretching [35]. Nodes are no longer selected to attach the force to a specific point on the pipe. A rigid plate is now modeled on which the force is placed to get a more realistic result. The plate is placed approximately in the middle of the pipe.

A force reactor controller was inserted into the analysis. This setting lists the forces applied to the rigid top plate that pushes the pipe down. The graph below shows that the force applied is right above 100 kN. Then this force decreases rapidly. The force decreases after hitting the pipe because the pipe then begins to collapse due to external pressure (3 MPa). When the pipe begins to collapse, the plate will no longer have contact with the pipe because the geometry of the pipe changes faster than the plate.

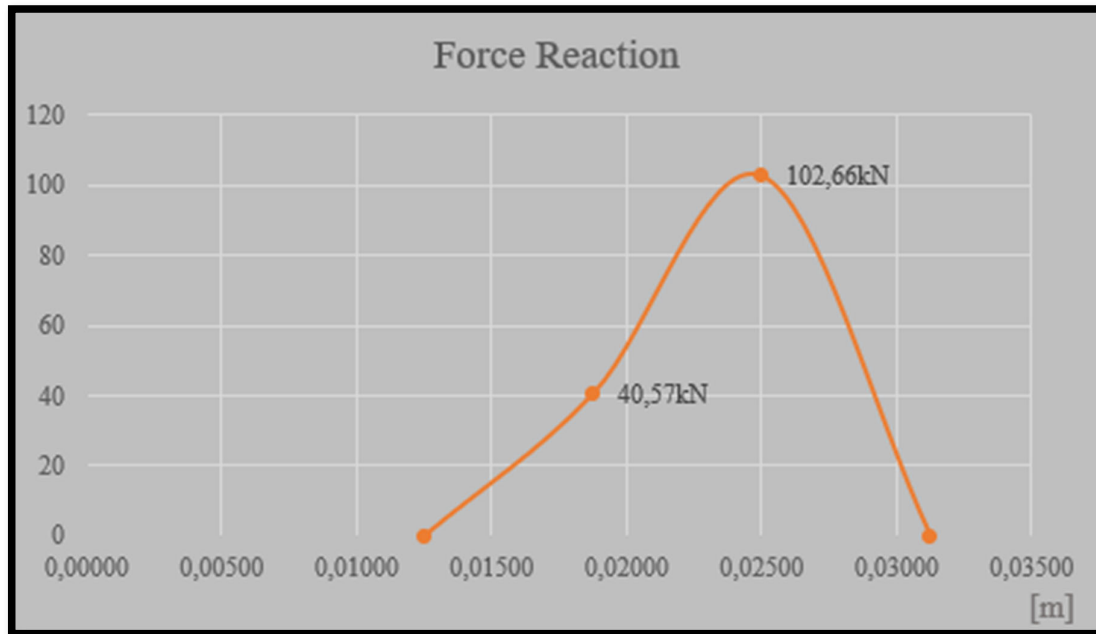


Figure 25 Force reaction

The contact force has been extracted, as shown in Figure 25. It is seen that when the pipe is loaded with 102,66 kN, slight deformation of the pipe occurs. It is still large enough that the pipe has begun to bend in the middle. There is a large enough force for the rest of the collapse to occur without the plate continuing to deform the pipe. How much the pipe is pressed down by 102,66 kN is shown in Figure 26.

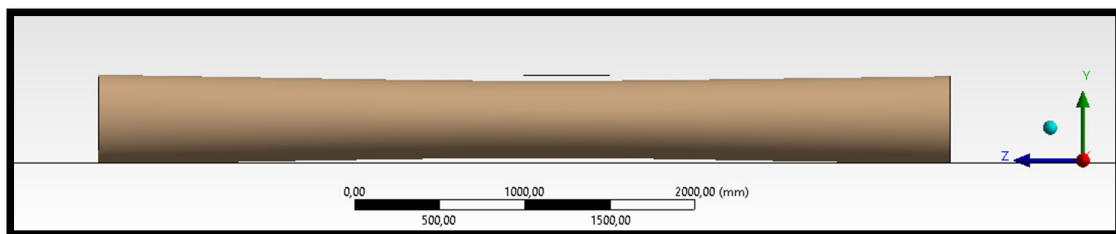


Figure 26 Result of force reaction

Furthermore, it is investigated how much energy is required to collapse the pipe using the indenter.

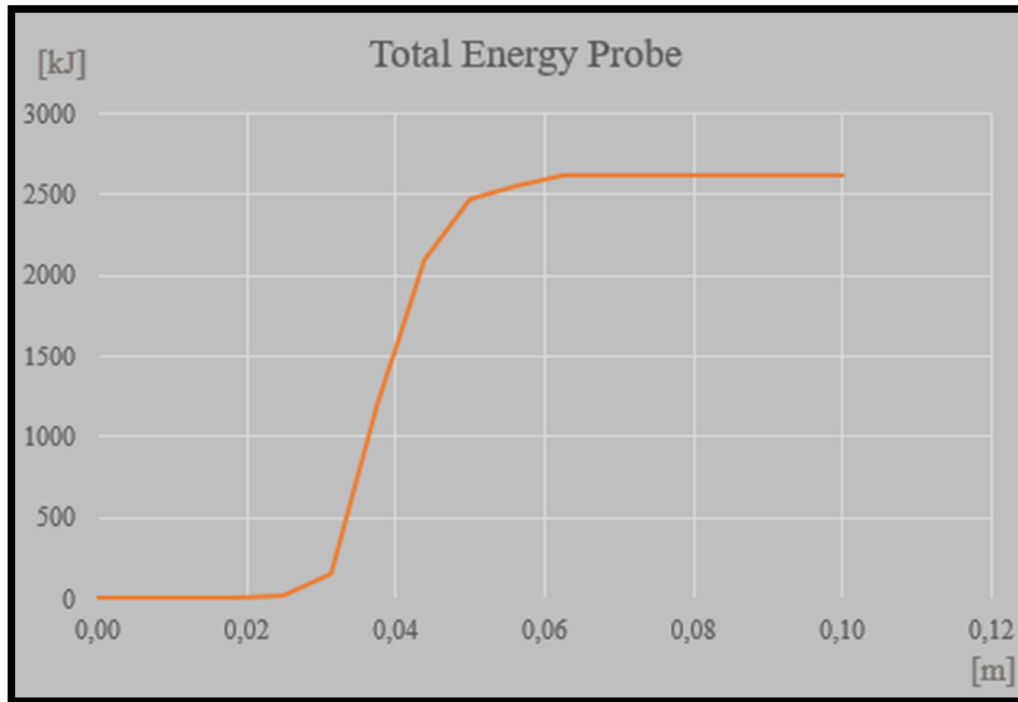


Figure 27 Energy results

In the area between steps 10 and 15 in Figure 27, the pipe completely collapses. An attempt has been made to present this collapse in Figure 28 and Figure 29. The anchor must hit with about 600 kJ for the pipe to collapse.

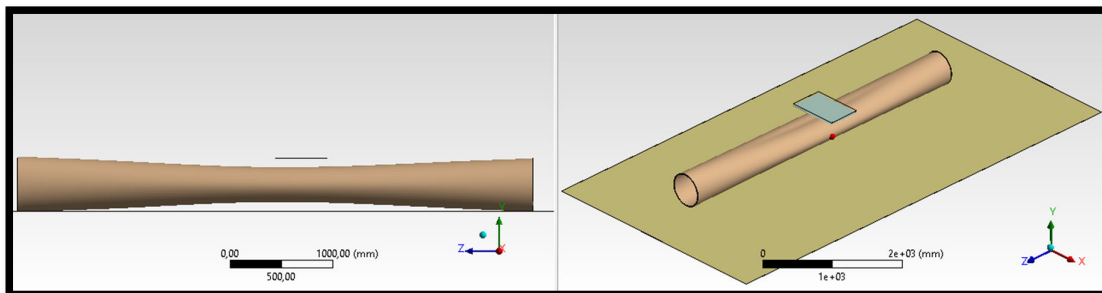


Figure 28 The tenth step

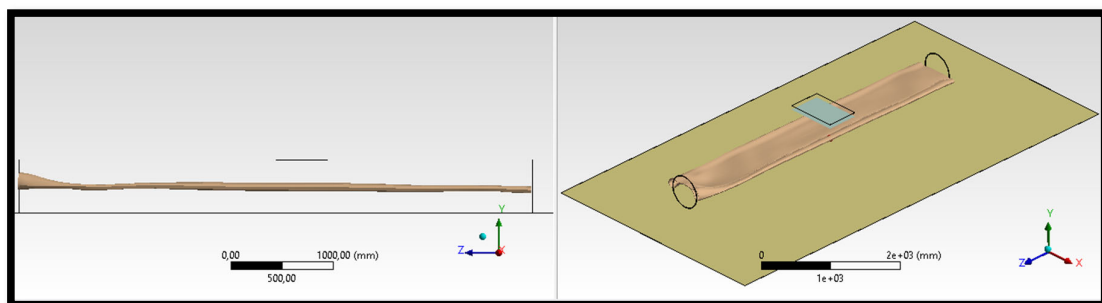


Figure 29 The fifteenth step

The total deformation is presented step by step in the figure below, Figure 30.

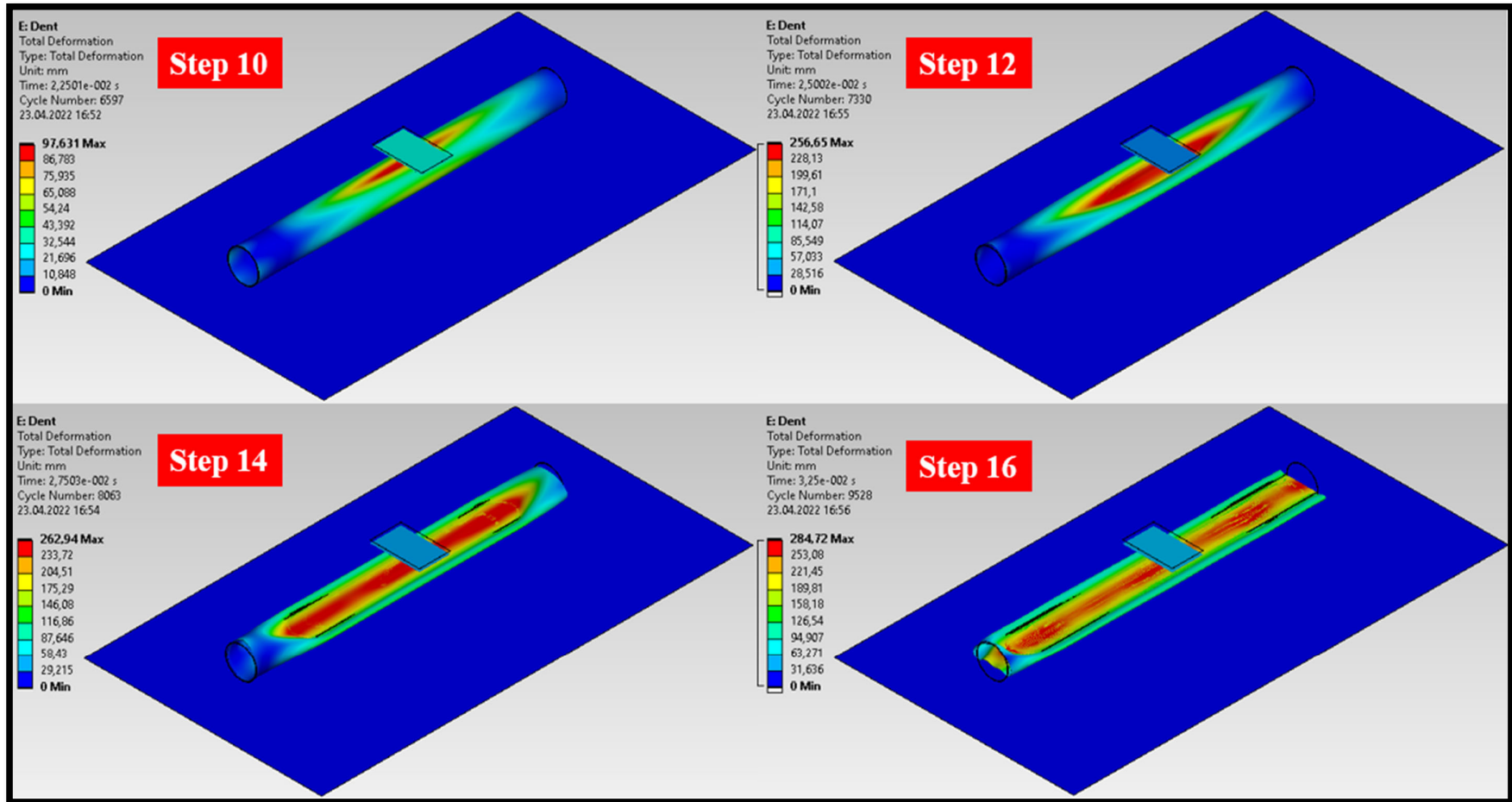


Figure 30 Total deformation step by step



### 6.7 Comparison between manual calculations and FE analyses

The comparison of the calculation from API and DNV has already been presented. Therefore, this chapter only deals with comparing the energy calculations that have been performed.

In Chapter 6.5, manual calculations were made for energy absorption. This calculation is based on the object hitting the pipe being sharp. The plate in ANSYS is half a meter wide, and it turns out that far more energy and force is required than calculated in manual calculations, reference to Table 12 and Figure 25, and Figure 27. Other than that plate, other simplifications have also been made in the FE program that can significantly impact the result. Although there are significant gaps between the results, both are considered valid. A comparison between the actual numerical answers will not be valid in this case, as the geometries hitting the pipe are vastly different.

### 6.8 Practical execution

In previous chapters, it has been investigated whether it is possible to collapse the pipe. Since it has been shown that this is possible, it is time to look at how this could be done in practice.

Draining the pipe for water can be done in several ways. First and foremost, all calculations are based on the inner pressure of the pipe being zero. This boundary is set to create the most significant possible differential pressure. As mentioned, all pipes must be flushed before disconnecting. Typically, the water is not pumped out of the pipeline if it remains on the seabed. To empty the pipe in this scenario is essential.

The pipe can be cut into shorter spools to simplify the pumping operation.

Cutting the pipe will incur a higher cost because both a surface vessel and an ROV will be required. There are different cutting tools, but the diamond wire saw is an effective tool, as mentioned earlier in the report. For cutting the pipe, ROVs equipped with a saw can be used. Relevant tools can be rented in the open market.

After the pipe has been cut to predetermined lengths, the pipe must be closed at both ends. Among other things, it can be welded on flanges at both ends, but this will require much equipment and is time-consuming. There are also different methods here. The most effective method is to use a clamped blind flange or blind hub. Several companies supply such flanges, including products from the company tp-products [36]. In addition, IK-Group supplies subsea plugs up to 36 ", which can have a design pressure of up to 600 bar. These plugs are designed

to fit an ROV operation, and the water depth of the plugs has no limits. [37]. The plug is equipped with a non-return valve to ensure that the water only flows out.

Air is then pumped in from the opposite end of the pipe section. It can be advantageous to have a PIG in the pipe as a barrier between the wet and dry sides. A technical explanation of such a plug is attached in APPENDIX B. The plug attachment is for an 8 " plug, but 16 " will work the same way. The air pressure must exceed the pressure on the seabed. A suggestion may be to have a compressor on the surface vessel that sends the air down and into the pipe. When the air pressure has been reached, and the water has been forced out, it should be possible to bleed off the pressure. One way this can be done is to have a pipe connection or hose connection to the vessel where a bleed valve is installed.

Many options can create a dent in the pipe. An alternative is to drop an anchor on the pipeline. Another way is to make an object that can be dropped on the pipe in the same way as, for example, concrete mats are installed on the seabed utilizing construction vessels (CSV). Other surface vessels may be relevant in operations where heavier objects are required to create the dent in the pipeline.

## 6.9 Discussion

Results and comparisons are presented. The next step is to discuss results from studies on this idea. First and foremost, collapsing a pipe is based on an undesirable event, and it is considered that pipe collapse should not occur even before the pipes are manufactured. No similar ideas have been found. Collapsing the pipe is considered an advantage to using smaller rock masses to cover the pipe in areas where this is necessary. On the other hand, this process must be repeated for each step, where there is a buckle arrestor.

Three different methods have been used to calculate whether the pipe is collapsing, whether the collapse will continue, and how much pressure is required to collapse the pipe. The results show that the method is feasible but that external forces are required to collapse the pipe. At least 102 kN is required to collapse the pipeline, ref Figure 25. The positive result from the calculations is that using the formulas from both API and DNV, it turns out that the differential pressure about the propagation pressure is large enough for a collapse to be possible. However, there are no large margins, so it is recommended to take a new check, possibly calculating the wall thickness of the pipe after the end of service time. A smaller wall thickness can improve margins.

The calculations do not consider that the pipe is covered with concrete and other coatings. It is assumed in the calculations that these coatings will not change the results. This is a rough assumption, but there are projects internally in Equinor that aim to test how much this will affect the collapse and propagation pressure. The coatings should be investigated if this method is to be used.

There can be countless reasons for the differences between manual calculations and analyzes in the FE program. First, the formulas are simplified so that it should be possible to calculate them. Secondly, several simplifications have been made in the FE analysis. Perhaps the most crucial factor that has been simplified in the FE analysis is the seabed. The pipeline is supported at the bottom of a plate as the analysis is run. This simplification of reality can have a significant impact depending on how the seabed material is. If the seabed is soft sand, it will have a different impact than if the seabed is made of stone. If the seabed is of sand, it can not be said with certainty that the pipe will collapse. Here the pipe may only be pushed further down into the seabed.

Another factor that turns out to be important is the object's geometry to hit the pipe. This report requires more energy to collapse the pipe if the object has a larger width.

#### 6.10 Part conclusion

In this method, several assumptions and simplifications have been made. This report is based on pipes laid on the seabed without being covered. The method will, therefore, not be suitable for all pipes. It is concluded that this is a method that can be used in some areas, where calculations show that it will be possible to implement.

Millions of Norwegian kroners are spent on covering with rock mass for larger intact pipelines [38]. If the pipe is flattened, it will be an economic gain as it will require less gravel to cover the pipeline. It is proposed to refill the collapsed pipe with rock. In areas with high activity and, therefore, a greater risk that the pipeline may be to the detriment of other sea users.

It is further concluded that nothing can be said about its importance if the pipe is placed in soft sand or something other than straight on stone.

Finally, it is concluded that many factors need to be investigated further before choosing this solution. What should be investigated further is mentioned later in the report.

## 7 Cost, emission estimates

Several methods have now been investigated. It is time to compare the results of the different methods. Early in the report, a consequence matrix contains multiple assumptions and opinions about cost, whether the method is feasible, and other assumptions. Now that the methods have been looked at more closely, it will be possible to set up a more factual matrix, although some assumptions must still be made. The first matrix contained numerical values for the various consequences. Based on previous studies, the forthcoming matrix will contain calculated values for the consequences where this is relevant.

In this chapter, the pipeline is defined the same way as the rest of the report. The outside diameter is thus 20 inches with a length of 200 km, where the pipeline is located at 310 meters sea depth. Additional information on the pipe is presented in Table 6.

### 7.1 Cost for each method

Calculations have been made concerning costs for five different cessation work methods. Here, the cost estimates are based mainly on internal documents in Equinor. Other than internal sources, the Impact assessment for offshore decommissioning by Norwegian Oil & Gas is used in this section, where uncertainty in the calculations is explained [39]. The uncertainty in the costs will always exist before a project is fully integrated. Earlier it was said that 30-40 percent uncertainty was realistic to calculate. Recently, it turned out that a higher percentage of uncertainty should be used in premature cases. Therefore, 50% of the total cost has been added for all five scenarios in this report. It is also important to note that the cost estimate is a small part of the report, and some assumptions have been necessary due to the time limit of the thesis. Other simplifications and assumptions are further explained in the discussion chapter, Chapter 8.

#### 7.1.1 Cost for trenching

The first priced method is trenching, estimated in Table 14 below. *Trenching* is a method used to lower the pipe into the seabed if it has been decided that the pipe will remain on the seabed. As pre-activities for the operation, it is planned to carry out a pre-survey with an ROV to document the status of the pipeline and identify debris, boulders, and rock dumps. The pipe will then be cleared of debris and boulders and moved rocks away. Vessels such as Edda Flora equipped with an ROV can be used here. It is assumed in the cost estimate that the transit time to and from the work area will be about one day [38].

Furthermore, the actual trenching operation is estimated the cost just under NOK 1 million per kilometer. Ships with a high bollard pull can be used here, for example, BOKA Falcon. It is also added that a visual inspection of the pipe should be done 3-5 years after the actual plowing operation is performed. If the inspection demonstrates that the pipeline is stable, no more surveys will be required. 50% uncertainty is only added to the total cost of the operation [39].

Table 14 presents the cost estimate for trenching, including 50% uncertainty.

*Table 14 Cost estimate for trenching*

Trenching [38]		
	Cost [NOK/km]	Cost [MNOK]
<b>Pre-survey, boulder/debris clearance and rock dump dispersal</b>	126444	25
<b>Burial operations (ploughing) and post survey</b>	923679	184
<b>Survey, ROV after 3-5 years</b>	19774	4
<b>Total Cost incl 50% uncertainty</b>		315

#### 7.1.2 Cost for leaving the pipe in-situ

The following investigated scenario is to leave the pipe on the seabed without covering it or digging it down. The estimate is given in Table 15. Since it has not been considered that the pipe must be cleaned before the pipe is left, the only thing that is included in this cost estimate are future examinations using ROV. In the aftermath of abandonment, inspections should be made to ensure that security in the area is maintained. Surveys should be carried out regularly, and it has been chosen to estimate that it is carried out every 20 years for 250 years [40]. Even though only surveys have been set up for 250 years, it is not expected that the pipe will be corroded away after this period. It has been chosen to use this limitation because it is considered that one has a good enough overview of the pipe condition after these surveys. Two hundred fifty years is a rough assumption, which can be changed if it turns out from the inspections that the pipe should be removed or if the laws are changed. In this method, 50% uncertainty is also considered, although there may be more significant uncertainty in some other methods. The 50% is also included because there is a chance that unforeseen things can happen in the future. By this means, repairs or the frequency of the surveys must be increased. It is possible that the uncertainty could have lowered considerably after the first survey, as this will make the situation more transparent. Table 15 presents the cost estimate for leave the pipe in situ, including 50% uncertainty.

Table 15 Cost estimate for leave the pipe in-situ

Leave the pipe in-situ [40]		
	Cost [NOK/km]	Cost [MNOK]
<b>Survey, ROV</b>	19774	4
<b>Survey repeated every 20 years 250 years</b>	257062	51
<b>Total Cost incl 50% uncertainty</b>		83

### 7.1.3 Cost for reverse cathodic protection

Additionally, an attempt has been made to set up a cost estimate for the first idea presented in this report, reverse cathodic protection. The estimate is provided in Table 16. It was concluded early in the report not to spend more time on this method, yet many possibilities have been described that can be used to speed up the corrosion time, and it has therefore been chosen to include it here. One of the first methods was to install cathodes on the pipe. Therefore, the estimate is based on installing cathodes, not installing a power system or other options.

Trenching study for the Valemon Rich Gas Pipeline from Equinor has been used for mobilization, pre-survey, and demobilization [38]. Since the method has not been used before, there is a good chance this is one of the methods containing tremendous uncertainty. In this method, it is primarily assumptions. It is assumed that the same type of vessel and ROV that performs the survey during the trenching operation can be used here. Furthermore, an assumption has been made to install the cathodes where it is said that cathodes must be installed every 3 kilometers and that such an installation will last for 24 hours. It should be possible to make cathodes that can be installed using a bolted connection to shorten the time, but at the same time, there is a good chance that the pipes have several protective layers. Therefore, it is considered that the protective layers must be removed to be able to install the cathodes. The uncertainty here is also calculated at 50%, as for the other methods. It is still considered a realistic assumption based on the added extra time during the installation of each cathode.

Table 16 presents the cost estimate for the reverse cathodic protection, including 50% uncertainty.

Table 16 Cost estimate for reverse cathodic protection

Reverse cathodic protection [38]		
	Cost/km [NOK/km]	Cost [MNOK]
<b>Mobilization</b>	20674	4
<b>Pre-survey ROV (4 km/h, 200 km)</b>	7970	1,6
<b>Cost for cathodes (4 Kg, 400 NOK/Kg, ref. Chapter 5.3)</b>	533	0,1
<b>Operation, Install cathodes (every 3 km, each lasting 24 h)</b>	255043	51
<b>Demobilization</b>	17904	3,6
<b>Total Cost incl 50% uncertainty</b>		90,7

#### 7.1.4 Cost for removing the pipeline

Presented in Table 17 is the method "Remove the pipeline". Previous studies have estimated the cost of removing the pipeline [40]. This report considers the use of reverse S-lay to remove the pipeline. The S-lay method must be used because the pipe is large, 16 ". It has not been considered that the pipeline may cross other pipelines. Whether these areas should remain on the seabed and possibly covered if it does should be investigated. Removing the pipeline is the method that is the most time-consuming. At the same time, it has a reasonably high cost per kilometer. The total cost is relatively high compared to the other methods presented in the report, but it will be definite once the pipeline has been removed, and there will be no need for future surveys.

Table 17 presents the cost estimate for removing the pipeline, including 50% uncertainty.

Table 17 Cost estimate for removing the pipeline

Remove the pipeline [40]		
	Cost [NOK]/km	Cost [MNOK]
<b>Complete removal (reverse s-lay method)</b>	10376647	2075
<b>Total Cost incl 50% uncertainty</b>		3113

#### 7.1.5 Cost for forcing the pipe to collapse

The last cost estimate deals with a different idea to force the pipe to collapse, see Table 18. Like reverse cathodic protection, this method contains many assumptions and high uncertainty. It is assumed that an anchor is used to collapse the pipe. Furthermore, it is assumed that the same survey vessel can be used in this operation as for the trenching method and assumed for the reverse cathodic method [38]. The price will then be equivalent for

collapsing the pipe and pre-survey, boulder/debris clearance, and rock dump dispersal. This simplification is made because it is assumed that the anchor must be dropped every 3 kilometers, i.e., 66 times. For this reason, it is also assumed that the speed of the surface vessel will be  $\frac{1}{4}$  of a survey vessel with a speed of 4km/h.

When it comes to the line where post-survey is calculated, it is assumed that this is an ROV that runs slowly over the pipe, with a speed of 1km/h [38]. A slower ROV is assumed to be necessary to perform a thorough pipe inspection.

One of the most uncertain elements in this cost estimate is whether it will be necessary to cover the pipe after a collapse or whether it may remain as it is. The cost estimate assumes that the pipe is not to the detriment or danger of other sea users when it collapses.

Table 18 presents the cost estimate for forcing the pipe to collapse, including 50% uncertainty.

*Table 18 Cost estimation for forcing the pipe to collapse*

Force the pipe to collapse [38] [40]		
	Cost [NOK/km]	Cost [MNOK]
<b>Survey, ROV</b>	19774	4
<b>Mobilization, Operation vessel</b>	20674	4
<b>Operation, collapse the pipe</b>	31882	6,4
<b>ROV, post survey</b>	31882	6,4
<b>Demobilization, vessel (including ROV)</b>	17904	3,6
<b>Total Cost incl 50% uncertainty</b>		36,7



## 7.2 Emissions for each method

Energy consumption and air emissions play an important role in deciding which method to finish work for offshore structures [39].

In this report, it has been chosen to emphasize emissions. Therefore, other important topics that should be studied further will be energy consumption, waste and resource utilization, and littering. In the handbook [39], the emission categories are divided into four categories, of which this report covers three of them. The first is marine operations. For the marine operations, discharges will be calculated primarily based on the vessels' data and the duration of the operations. The last two categories deal with onshore dismantling and material recycling. These categories are primarily about the amount of material to dismantle or recycle.

Emission is assumed to be only from the vessels and recycling, where it is further assumed that all vessels use MDO / MGO (Marine diesel oil / Marine gasoline) as fuel. It is important to note that there are many attempts to use less polluting fuel than expected in this exercise. All results for emissions from vessel operations can be reduced by using newer propulsion systems. Examples here could be biofuel, ammonia, electricity, hydrogen, or other lighter types of diesel.

MDO (marine diesel oil) distills marine fuels, including marine gas oil (MGO). This report assumes that the vessel in the operations consumes MDO / MGO, and the emissions are based on this. The emission factors (EF) for MDO were used due to information that vessels like Edda Flora consume MDO / MGO [41]. It is assumed that similar ships used for the operations use MDO / MGO.

Working day and daily fuel consumption assume 24 hours duration. Helicopter or other transport-related to change of personnel was not calculated.

CO<sub>2</sub> emissions were calculated from the fuel-based emission factor [42].

The limits for Sulphur content in fuel at sea in Emission Control Areas (ECAs) were reduced to 0.1% in 2015, including The North Sea [43]. During combustion, Sulphur reacts with oxygen and forms sulfur oxides (SO<sub>x</sub>), mainly sulfur dioxide (SO<sub>2</sub>) [42]. The average Sulphur content of MDO varies, and the global average in 2018 was 0,07%. The fuel-specific emission factor of SO<sub>x</sub> assumed a Sulphur content of 0,07% [42].

The emission of NO<sub>x</sub> is dependent on the engine type. In this report, a medium speed engine was defined as  $200 \leq \text{rpm} < 1000$ , while a high-speed engine was defined as  $1000 \leq \text{rpm}$  [44]. The emission factor used for NO<sub>x</sub> assumed the use of engines from 2000 and newer years [44]. An assumption was made in this report that the survey vessel is a high-speed vessel, while the plow and pipeline vessels are medium-speed vessels.

According to the ISO 8217:2017 Fuel standard for marine distillate fuels, including MGO, have a maximum density at 15 degrees C of 890 kg/m<sup>3</sup> [45]. Therefore, 1 ton of MGO equals 1,12 m<sup>3</sup> MGO. Emission factors were converted to ton/m<sup>3</sup> for CO<sub>2</sub>, SO<sub>2</sub>, and NO<sub>x</sub> [42], [44].

In Table 19, the emission factors were converted and used to estimate emissions.

*Table 19 Emission Factors*

Emission factors for MGO	
<b>CO<sub>2</sub> [ton/m<sup>3</sup>] [42]</b>	2,8625
<b>NO<sub>x</sub> [ton/m<sup>3</sup>] [44]</b>	High speed: 0,037 Medium speed: 0,05
<b>SO<sub>2</sub> [ton/m<sup>3</sup>] [42]</b>	0,0012

Furthermore, the various vessels are listed in Table 20, together with their fuel consumption.

*Table 20 Vessel's fuel consumption*

Vessel	Fuel consumption [m <sup>3</sup> /day]
<b>Survey [38]</b>	Transit: 25, DP & Survey: 10
<b>Plough [38]</b>	Transit: 28 DP & Survey: 25 Ploughing: 65
<b>Pipelay (for removal) [46]</b>	99,50

## 7.2.1 Emission to air, trenching

The emissions from trenching method were calculated and presented in Table 21.

Table 21 Emission, Trenching

Trenching					
	Daily Fuel consumption [m <sup>3</sup> ] [38]	Duration [days] [38]	Emission [t] = Fuel Consumption [m <sup>3</sup> ] · emission factor [t/m <sup>3</sup> ]		
			CO <sub>2</sub> [t]	NO <sub>X</sub> [t]	SO <sub>x</sub> [t]
<b>Pre-survey, boulder/debris clearance and rock dump dispersal</b>					
<b>Transit</b>	25	1	71,56	0,92	0,03
<b>Pre-survey</b>	10	2,1	59,64	0,76	0,03
<b>Boulder/debris clearance rock dump dispersal</b>	10	19,4	555,80	7,11	0,23
<b>Burial operations (ploughing) and post survey</b>					
<b>Transit</b>	28	3	240,45	3,97	0,10
<b>Ploughing</b>	65	42,3	7868,80	130,03	3,30
<b>Post-survey</b>	25	8,3	596,35	9,85	0,25
<b>Survey, ROV after 3-5 years</b>					
<b>Transit</b>	25	1	71,56	0,92	0,03
<b>Survey with ROV</b>	10	2,1	59,64	0,76	0,03
<b>Total Emission</b>			<b>9523,90</b>	<b>154,31</b>	<b>3,99</b>

### 7.2.2 Emission to air, leave the pipe in-situ

The emissions from the leave in-situ method were calculated and presented in Table 22. It was assumed that the use of MDO, not considering that future vessels will be able to use other fuel types or become more efficient.

Table 22 Emission, Leave in-situ

Leave in-situ					
	Daily Fuel consumption [m <sup>3</sup> ] [38]	Duration [days] [38]	Emission [t] = Fuel Consumption [m <sup>3</sup> ] · emission factor [t/m <sup>3</sup> ]		
			CO2 [t]	NOX [t]	SOx[t]
<b>Survey</b>					
<b>Transit</b>	25	1	71,56	0,92	0,03
<b>Survey with ROV</b>	10	2,10	59,64	0,76	0,03
<b>Survey repeated every 20 years 250 years (13 times)</b>					
<b>Transit</b>	25	13	930,31	11,90	0,39
<b>Survey with ROV</b>	10	27,10	775,26	9,91	0,33
<b>Total Emission</b>			<b>1836,77</b>	<b>23,49</b>	<b>0,77</b>

### 7.2.3 Emission to air, reverse cathodic protection

The reverse cathodic protection method emissions were calculated and presented in Table 23. The table assumes that the vessel used for installing cathodes is a standard survey ship.

Table 23 Emission, Reverse cathodic protection

Reverse cathodic protection					
	Daily Fuel consumption [m <sup>3</sup> ] [38]	Duration [days] [38]	Emission [t] = Fuel Consumption [m <sup>3</sup> ] · emission factor [t/m <sup>3</sup> ]		
			CO2 [t]	NOX [t]	SOx [t]
<b>Transit</b>	25	1	71,560	0,92	0,03
<b>Pre-survey ROV (4 km/h, 200 km)</b>	10	50	1431,25	18,30	0,60
<b>Operation, Install cathodes (every 3 km, each lasting 24 h)</b>	10	66,70	1908,33	24,40	0,80
<b>Total Emission</b>			<b>3411,15</b>	<b>43,62</b>	<b>1,43</b>

#### 7.2.4 Emission to air, remove the pipeline

The pipeline removal option emissions were calculated and presented in Table 25. Estimates are based on a previous study [40]. Fuel consumption is taken from internal studies in Equinor [46]. It is not included in separate calculations for transit for pipelaying vessels but assumed it had been included in previous calculations. Assumed that a pipelay vessel is used for this method and that the fuel consumption is equal for MGO and HFO [46].

For pipeline removal options, emissions were also estimated for recycling pipeline steel. Emissions for steel production were also calculated to compare recycling and new steel production emissions.

To calculate the emissions from the recycling of steel, first, the pipeline weight and total amount of steel in a pipeline of 200 km were calculated. In addition, the weight of the pipe in water is calculated. It is assumed that the density of the steel is 7850 kg / m<sup>3</sup>. The remaining factors are taken from Table 6.

$$Weight_{pipe} = \frac{\pi}{4} \cdot 7850 \text{ kg/m}^3 \cdot ((0,508\text{m})^2 - (0,473\text{m})^2) = 211,580 \frac{\text{kg}}{\text{m}} \quad (7.2.4.1)$$

$$Weight_{pipe,200\text{km}} = 42320 \text{ ton} \quad (7.2.4.2)$$

Emissions of CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>2</sub> per ton steel is presented in Table 24. The estimates were based on a guideline published by Institute of Petroleum, London [47].

Table 24 Emissions from standard steel for recycling and production

	Recycling		Production	
	[kg/t]	[t]	[kg/t]	[t/t]
<b>CO<sub>2</sub></b>	960	0,96	<b>CO<sub>2</sub></b>	1,89
<b>NO<sub>x</sub></b>	1,60	0,002	<b>NO<sub>x</sub></b>	0,004
<b>SO<sub>2</sub></b>	3,80	0,004	<b>SO<sub>2</sub></b>	0,006

For all options where the pipeline is deposited at the seabed or the material is not recycled after removal, there will be indirect emissions from replacing the lost steel of the decommissioned pipeline.

Table 25 Emission, Remove the pipeline

Remove the pipeline					
	Daily Fuel consumption [m <sup>3</sup> ] [46]	Duration [days] [40]	Emission [t] = Fuel Consumption [m <sup>3</sup> ] · emission factor [t/m <sup>3</sup> ]		
			CO <sub>2</sub> [t]	NO <sub>X</sub> [t]	SO <sub>x</sub> [t]
<b>Complete removal (reverse s-lay method)</b>	99,50	333,33	94939,58	1568,70	39,80
<b>Recycling of steel in existing pipeline (200 km)</b>			40627,20	67,71	160,80
<b>Total Emission</b>			<b>135566,78</b>	<b>1636,50</b>	<b>200,60</b>

## 7.2.5 Emission to air, forcing the pipe to collapse

The method's emissions that force the pipe to collapse were calculated and presented in Table 26. It was assumed that future surveys would not be performed.

Table 26 Emission, Force the pipe to collapse

Force the pipe to collapse					
	Daily Fuel consumption [m <sup>3</sup> ] [38]	Duration [days] [38]	Emission [t] = Fuel Consumption [m <sup>3</sup> ] · emission factor [t/m <sup>3</sup> ]		
			CO <sub>2</sub> [t]	NO <sub>X</sub> [t]	SO <sub>x</sub> [t]
<b>Pre-survey, ROV</b>					
<b>Transit</b>	25	1	71,56	0,91	0,03
<b>Survey</b>	10	2,10	59,63	0,76	0,02
<b>Operation, collapse the pipe</b>			0,00	0,00	0,00
<b>Transit</b>	25	1	71,56	0,91	0,03
<b>Operation, collapse the pipe</b>	10	8,30	238,54	3,05	0,10
<b>ROV, post survey</b>	10	8,30	238,54	3,05	0,10
<b>Total Emission</b>			<b>679,84</b>	<b>8,69</b>	<b>0,28</b>

## 8 Discussion

In 2022, European Union (EU) published a final report, "Study on Decommissioning of offshore oil and gas installations: a technical, legal, and political analysis [48]. The study thus contains what the laws in the different countries say about decommissioning and a comparison. Furthermore, possible solutions for what should be done are also presented. As in the previous reports, not much is said about the pipelines. The most important thing from the report is already known; they must be removed, left in situ, or covered. The report states that the danger to the environment if the pipes remain on the seabed is small spills of oil or other substances. There is thus no mention of the coatings the pipelines are often covered with. It is further stated that it is expected that the seabed will look the same after disconnection as before the installation took place. If removal of the pipelines will have a more significant impact on the environment than leaving the pipeline on the seabed, this should be a good enough reason for leaving in-situ. Although it is said that any emissions from abandoned pipelines are low, it is also said that due to the large amounts of pipes that remain, the outcome can be much more significant by looking further ahead. Interestingly, no new proposals for solutions have been presented, nor has much emphasis been placed on reusing the pipelines [48]. In this report, emphasis is placed on two new methods.

### 8.1 Reverse cathodic protection

Several factors were discussed for the first method, which involved reversing the cathodic protection in Chapter 5. It investigates this method, unaware of the amounts of plastic and offerings connected to the pipes. It was calculated that the pipe could corrode 0,01 mm per year if the anodes were removed. This calculation does not consider that the first layer of corrosion can delay further corrosion and that there is little oxygen in the area if this is not added. Due to limited knowledge of the subject, no precise calculations have been made on how much the corrosion time is reduced by installing cathodes.

On the other hand, it is assumed that the amount of stainless steel that must be installed as a cathode is unrealistically large. There are opportunities to work further with this idea. It can be connected to electricity or other processes to increase the corrosion time, but if the pipe is covered with concrete or asphalt, this will not corrode away in the same way. What should be done with the concrete if the method is used must be studied. The unknown factors regarding the concrete are one of the main reasons it was chosen not to look further at this method. Another reason why no more time was spent on the method is because it will require much

work from underwater vehicles and surface vessels. Not only that, but the anodes must be replaced with new material, and the suitable materials are also relatively high priced. The total cost will be high, and so will the emissions from the required vessels.

## 8.2 Imposed collapse

At first, it was thought that the pipe collapse would be enough, but if it turns out that there is still danger to other sea users, the pipe may need to be covered afterward. If it is necessary to cover the flat pipe with gravel afterward, it is considered that it will require significantly less volume of gravel than if the pipe was not collapsed in advance. Less volume of gravel will result in less cost for stone, sand, or gravel and further fewer emissions due to surface vessels.

The idea is good and based on information about the existing pipelines. Because the knowledge about the collapse of pipelines was minimal, much time was spent reading literature, standards, and previous attempts at the topic. Knowledge of the FE program used was also limited. The limitation in knowledge and time has resulted in both assumptions and limitations being made. Assumptions about a rigid seabed and that the temperature is 22 degrees Celsius have not been considered but is assumed to be no of importance. The fact that the seabed is ridged is a simplification, and if the method is to be used, this must be considered because a ridged seabed will cause tremendous damage to the pipe. It will be more challenging to collapse a pipe buried or lying in the sand instead of directly on a rock, as is intended here [49].

Similar assumptions are mentioned in the main chapter, but it is necessary to re-mention some of the factors that should be studied further.

One of the factors that are seen as most important to look at further is how concrete and other coatings affect the strength of the pipe. The coating has not been considered in this report. Calculations have been made for pipes that are not coated with concrete.

Another factor not considered is the forces that will act at the end of a propagated pipe spool. The force at the pipe end is an essential element. What will happen to a hub or valve at the end of the propagated pipe is so far unknown. It should be considered whether the pipe ends will withstand these forces or whether the pipe must be cut at both ends before such an operation is performed. If the pipe is cut into a spool before propagating, it is another factor that has not been investigated. If the pipe collapses, it must be possible to say how clean the pipe is before the operation. How clean is the pipe after it has been cleaned?



Furthermore, a completely different factor that has a significant degree of influence is which material quality is delivered. When a pipe is produced, such as X65 carbon steel used in this report, the requirement is that factors such as the elastic modulus minimum must be 210 GPa as a minimum. A minimum requirement means that the elastic modulus delivered can be higher, for example, 250 GPa, which will impact the calculations for collapse. Therefore, it will be significant to make the calculations based on the material certificates provided for the pipe in question. Furthermore, it can then also be advantageous to check whether the thickness or ovality of the pipe has changed over its lifetime. In this report, it is assumed that the thickness and ovality of the pipe are the same as initially. If the thickness has decreased and the ovality has increased, it may be less demanding to collapse the pipe.

As mentioned in the previous section, it can be advantageous that the thickness of the pipe is reduced if the pipe is to collapse. Leaving the pipeline on the seabed for a while with open ends may result in pipe corrosion. The corrosion thereby will reduce the pipe thickness. The decrease in thickness can be a great benefit to creating propagation collapse. Here is an opportunity to combine the two mentioned options from this report.

### 8.3 Cost

All tables showing costs for each method are presented earlier in the report. A graphical overview has been set up in Figure 31 to compare the results, showing what percentage each method will cost compared to all methods' total price.

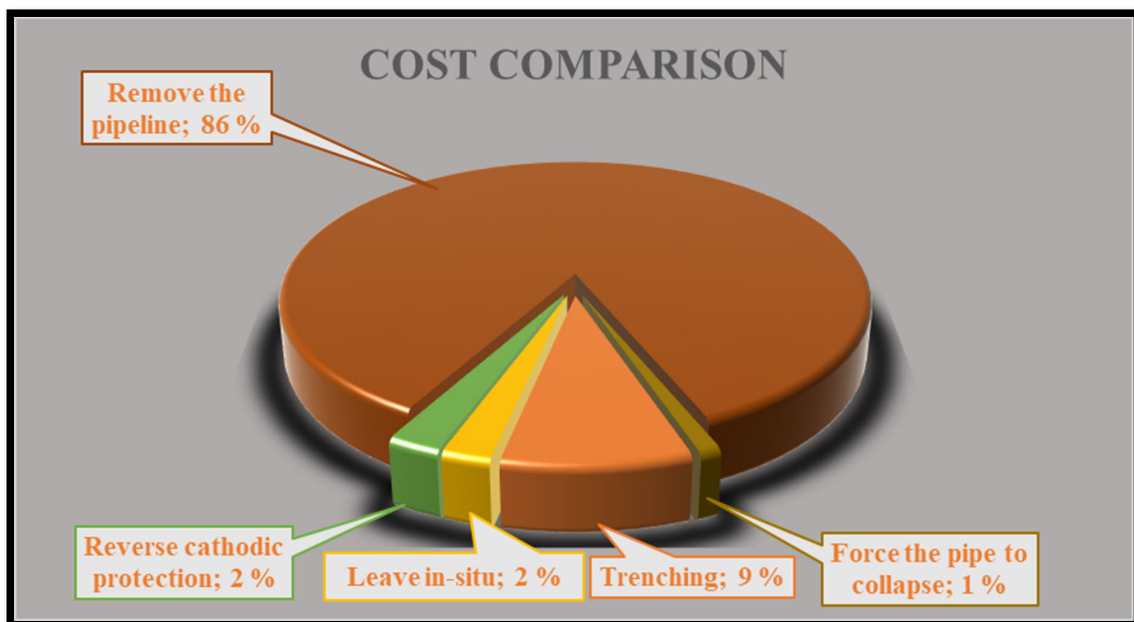


Figure 31 Cost comparison for each method

As expected, the rate for removing the pipeline is the highest cost, resulting in 86%. This is not a surprising result, as this operation will have a long duration, and it is by far the most comprehensive operation. The second most expensive operation is trenching. This method has relatively low uncertainty in the cost estimate compared with the two separately presented methods. It is important to note that the costs of own methods have a higher uncertainty than the other methods.

Furthermore, Equinor's studies have used pounds in the calculations. This report has decided to convert pounds sterling (GBP) into Norwegian million kroner (MNOK). The converting was done on 20.03.22, where 1 GBP corresponds to 11,53 NOK. The pound may change if this report is used in recent times, but it can not be guaranteed that prices will be the same. The costs used are based on prices stated in 2020. Therefore, it is recommended to only use the costs in this report as guidance and possibly as a project budget before the costs can be replaced with more detailed estimates. Another factor that may be important is that helicopter transport is not calculated in the estimates. For operations over more extended periods, this may be necessary to consider the personnel transport.

Another factor worth mentioning is that the estimated costs do not account for downtime due to weather conditions or seasons. The weather conditions should be studied more closely, especially if some of the methods are used over several months.

Costs for cleaning the pipe are not included in any of the cases. Cleaning is neglected because this cost is assumed to be equal for each method.

A final factor that is not included in the cost estimate is recycling. It will not be possible for pipes covered with concrete to recycle the concrete, but it can be removed from the pipe and used for other purposes.

Limited information regarding the cost of recycling has been found. Therefore, if the pipe is removed, this needs to be clarified. For that reason, it is also not known how much the company could get back from money if the plastic and steel were reused. These factors should be considered in a further impact assessment.

The estimated emissions and costs for the options that do not include removal of the pipe may hold potential future costs and emissions related to removal if there are changes in laws and regulations that require pipelines to be removed.

#### 8.4 Emissions to air

The calculations for emissions are presented earlier in the report. It is chosen to present an overview that illustrates the difference in emissions for each method graphically. The emissions of CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>x</sub> are presented below, respectively. For CO<sub>2</sub> emissions, removing the pipe or trenching it down will give the highest emissions. As for cost, there will be some uncertainties in the calculations. A realistic uncertainty will be about 50% in this case. According to this report, the last method, where the pipe collapses, will have the most negligible emissions, but on the other hand, this is one of the two methods that contains the highest uncertainty.

For emissions of NO<sub>x</sub> and SO<sub>x</sub>, it is much clearer that removing the pipeline will give the most emissions. See Figure 32 and Figure 33. However, it is imperative to remember that if the pipeline is disconnected and removed, it will be possible to recycle the mass of the material. Recycling can be of great benefit and should be considered when choosing which method to use.

The remaining methods in these graphs look almost insignificant. As mentioned below in the figures, some simplifications and assumptions have been made. These can significantly impact the results that have now been discussed.

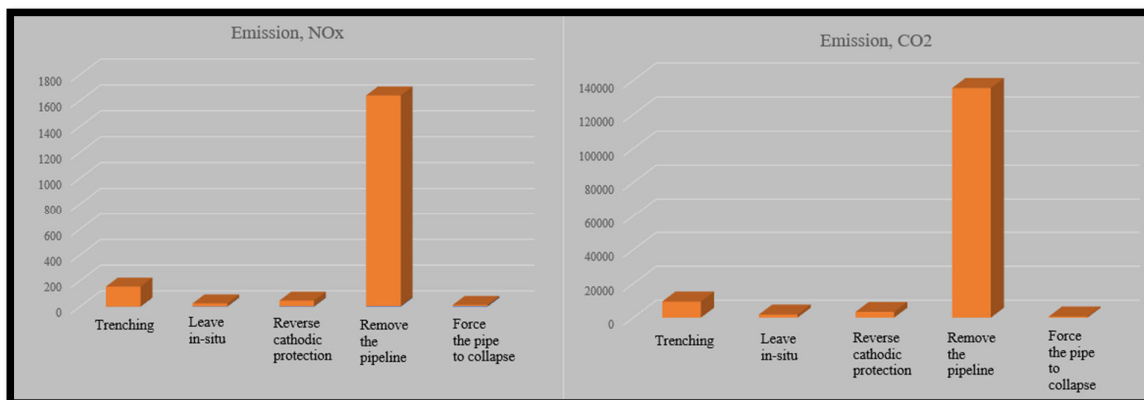


Figure 32 Emission of CO<sub>2</sub> & NO<sub>x</sub> for the five methods

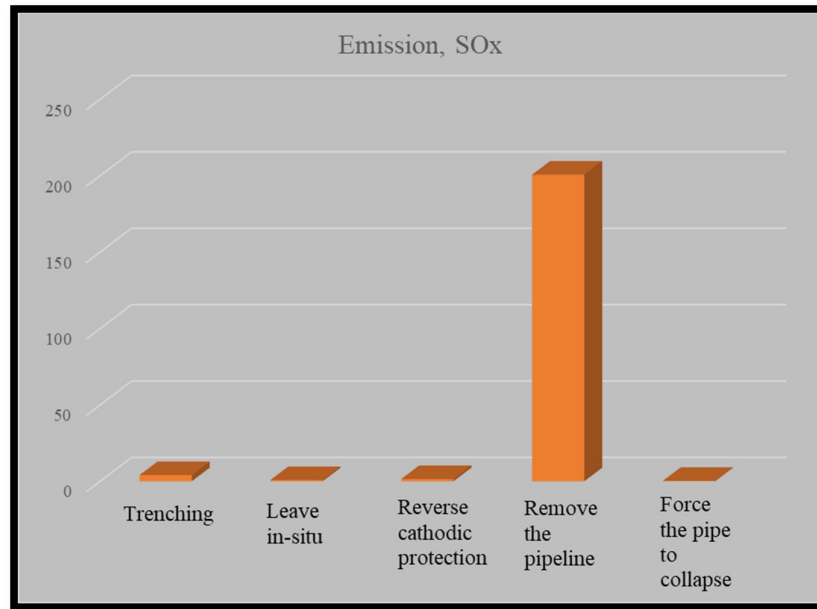


Figure 33 Emission of SOx for the five methods

For all options where the pipeline is deposited at the seabed or the material is not recycled after removal, there will be indirect emissions from replacing the lost steel of the decommissioned pipeline. The emissions from recycling are significantly lower than from producing an equal amount of new steel [47]. The reported emissions from the recycling of steel vary significantly, and according to IOP, the reported emissions range from 177-960 kg CO<sub>2</sub>, 1-0,6 kg NO<sub>x</sub> and 0,25-3,8 kg SO<sub>2</sub> per ton of steel [47]. The upper limit value was used to estimate emissions from recycling, and therefore, the actual emissions may be lower than those estimated.

For the chosen pipeline of 200 km, the production of the steel cause emissions of approximately 80000 tons of CO<sub>2</sub>, 148 tons of NO<sub>x</sub> and, 233 tons of SO<sub>2</sub>, see Table 24. The steel recycling in a corresponding pipeline will entail emissions of approximately 41000 tons of CO<sub>2</sub>, 67 tons of NO<sub>x</sub>, and 161 tons of SO<sub>2</sub>. Recycling the steel from the pipeline will add additional emissions to the operations. The removal of pipelines and recycling of the pipeline steel will seemingly account for the most significant emissions to the air. When considering that emissions from recycling are significantly lower than the production of new steel, the total emissions will be lower. However, the direct emissions of the decommissioning operation that includes recycling the steel are higher. Therefore, disposal at sea will result in higher emissions when considered that new steel must be created.

## 9 Conclusion and further work

This chapter presents the concluding part of the report. The report was written to investigate if it is possible to use other methods as cessation work for deep-water pipelines than current known solutions. The methods should not only be innovative, but the goal was that the methods should be more environmentally friendly and cost-effective than known methods. Results have been presented for the calculation of air emissions and the cost of the methods. Nevertheless, it should be considered that the costs can change drastically, and it cannot be said that the costs will be the same in the future.

Risk analysis should be an essential factor in choosing a method. No time has been spent setting up risk analysis for each method. The risk of littering in the sea should consider any coatings containing plastic or other materials. For all methods where the pipe remains on the seabed, polluting gases should also be considered if the pipe is not thoroughly cleaned, or there is a risk of polluting gases forming when the pipe begins to corrode.

This report cannot say precisely how much the reverse cathodic protection method will affect the corrosion process of the pipeline. Nevertheless, it can be said that if the cathodes are large enough, it will be possible to accelerate the corrosion process using this method. In other words, for the first idea, it is concluded that much work remains if reverse cathodic protection is to be used. It will be crucial to make this method more effective for it to work. This report concludes that the method is not satisfactory as presented in this report. It will be too time-consuming to use this method, as presented in this report. Practical experiments should be done, and new calculations for the time it will take to corrode the pipe if cathodes are installed. Several possible measures have been presented that can be taken to speed up the corrosion process. These measures can be studied further. If this method is investigated further, it should be calculated how much it is possible to accelerate the corrosion time by installing cathodes. However, other possibilities such as connecting power should also be considered.

It is further concluded that several possible methods can be investigated further. Collapsing the pipe has excellent potential, and the calculations and analysis program results indicate that the method can work. However, it is recommended to test the method further in practice. Several factors must be investigated further, such as the protective coatings' impact on the pipe and what substrates it is in the potential area. Nevertheless, the author believes this

method is well suited in areas with high activity and where there is a danger that the pipeline will later be to the detriment of other sea users.

In the long run, it is difficult to conclude which method is best suited in terms of the environment, cost, and detriment to other sea users. From a comparison of cost and emissions to air that has been made, removing the pipe looks the least appropriate. Nevertheless, it is essential to note that for this method, the steel can be reused. Remelting of steel is far more environmentally friendly than producing new, which should be considered when choosing a method. Although the two proposed novel methods are relatively environmentally friendly and cost-effective, further studies should be made to reduce the uncertainty associated with the methods.

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## APPENDIX A: ANSYS pre-work

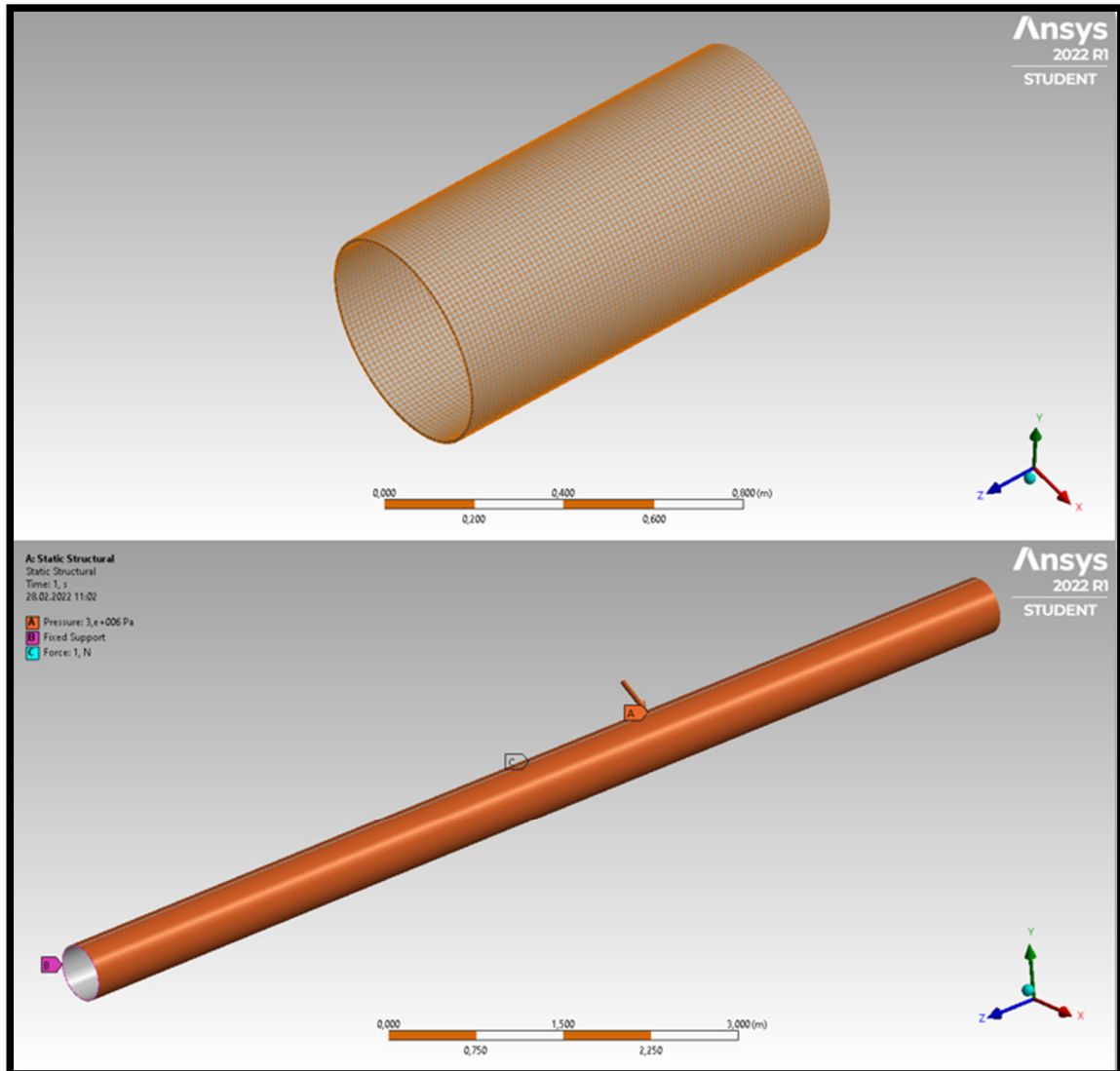


Figure 34 First set-up in ANSYS

Figure 34 illustrates the pipe. External pressure has been applied as approximately 3 MPa. Furthermore, a force is also applied in the middle of the pipe, which illustrates the local buckling force. For this force to give as accurate results as possible, a slight groove has been made that runs along the entire pipe. This groove will be the surface the force hits the pipe in. The force on the pipe is entered as 1 Newton to find out later in the analysis how high this force must be to make the pipe collapse. The force illustrated as "C" in the figure now acts vertically on the surface of the pipe. No examples have been found that others have used this method, but an attempt is still being made to see if this can be an accurate enough method.

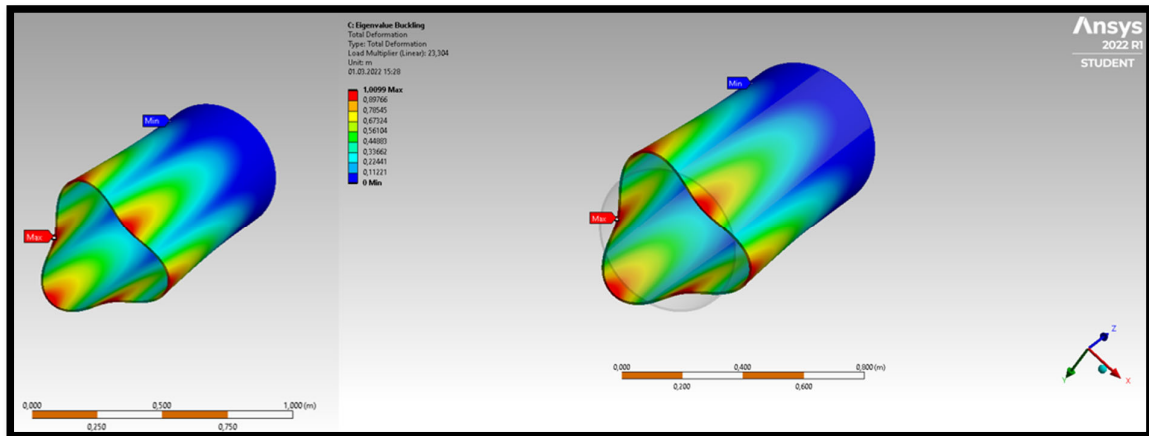


Figure 35 Results from first attempt in ANSYS

Figure 35 shows that the deformation is approximately 1.00 m if the pipe is loaded with 23.304 N. Since the results of inserting 1N as force show that this must be multiplied by 23,304N, it is chosen to change the force to 23,304N. After the analysis has been run with higher forces, the pipe is collapsing. Figure 36 shows the deformation of the pipe and the fact that the original shape is illustrated as a faint circle inside the deformation.

This method will only show minor deformations, although it appears that the pipe shape changes considerably. A node force is applied before a high force of 199999N is applied to look at the actual deformation. In Figure 36, it is shown where the force is applied. This force is gradually reduced to find a more accurate force.

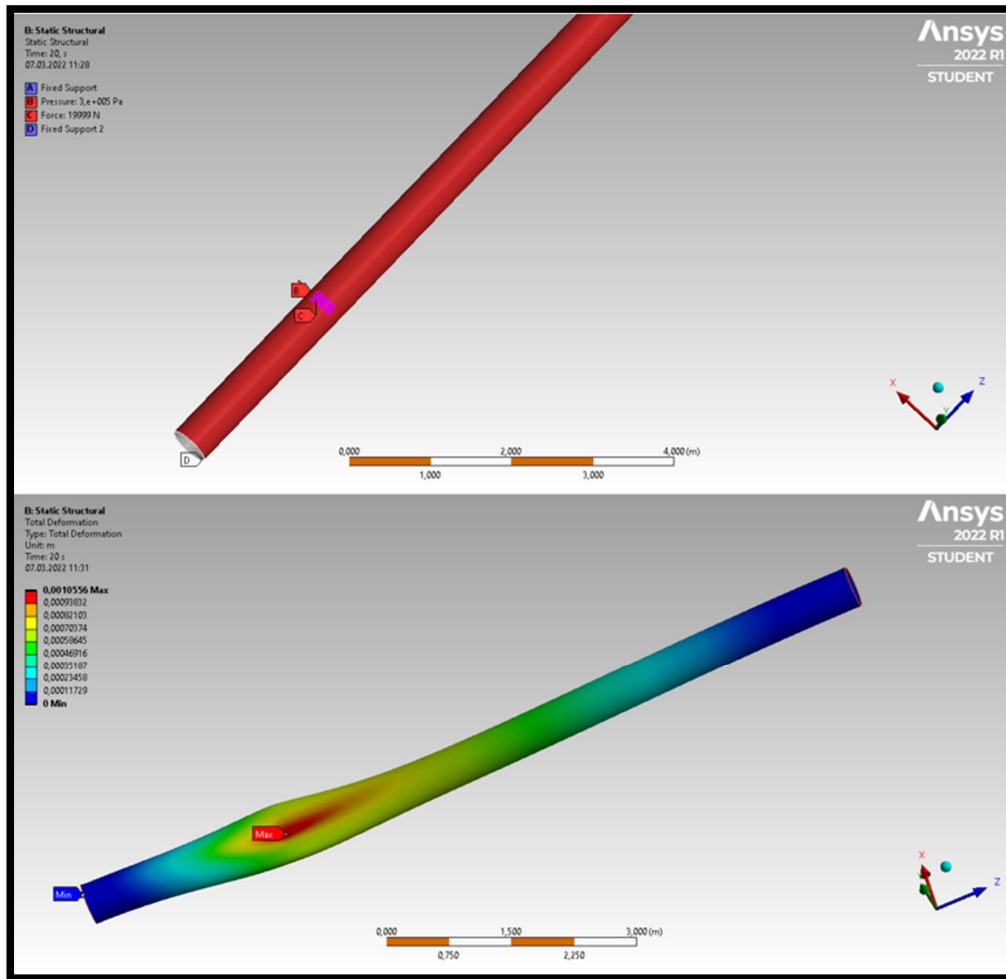


Figure 36 Results from second attempt in ANSYS

The load is marked pink in Figure 36. It is shown that the pipe is folded in the area where the force is applied.

If the power is reduced considerably, it is seen that the program manages to provide a more realistic solution. Still, the pipe does not appear to be propagating.

It is chosen to divide the pipe into four zones. Now, it is possible to insert the force between the zones at the top. Below is how this was done. The pipe is now modeled with four-node shell elements. [31].

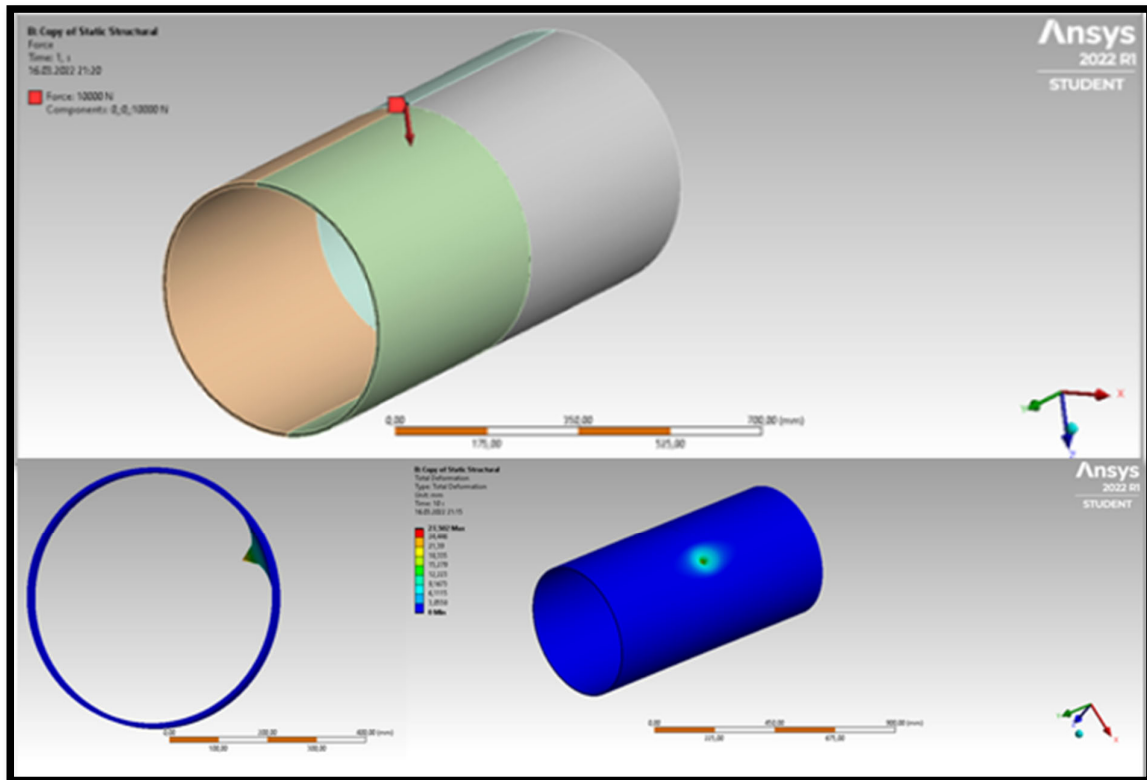


Figure 37 Force in node

Figure 37 presents the use of nodes for power and pipe support. The nodes are used, among other things, to support the pipe at the bottom. Usually, the pipes rest on the seabed, while the pipe will lie above the seabed, attached to the bottom, such as in a fixed beam.

The force that will hit the pipe will not be so sharp that it only hits at one point. If this is the case, it is shown in the figure above how ANSYS chooses to analyze the scenario.

As shown above, this analysis may not be realistic enough that the pipe will collapse and that the collapse will propagate, regardless of the force used. The program only analyzes the point the force hits, and it will eventually end up with a small hole in the pipe.

APPENDIX B: Flush Plug



## **8" Temporary Flushable Abandonment Plug**

The plug (s) is based on our standard sealing plugs, with sealing provided by compression of the packers and mechanical support by high friction packers

The high flow requirement for the plugs is secured by two off 2" ports and the flushing pressure of up to 2 - 4 bars are secured by the high friction packers giving a firm mechanical connection between flowline and plug.

It should be noted that there is not possible to offer a reliable sealing solution for 8 or 12 bar ( appr 3 – 5 Te end cap load ) without the use of mechanical grip, with corresponding grip marks.

Based on this we propose to use high friction packers and 2 off 2" check valves to secure low pressure drop during the flushing.

The crack opening of 6 bar will give a similar problem and to cope with that we propose to include ball valves after each check valve.

Please note that this propose method is a standard way for flushing plugs that we normally deliver for such tasks.

### **General description all the plug**

Pipe material:	Carbon steel
Pipe cut misalignment:	Up to 5°
Plug total length	Appr 600 mm
Plug hard OD:	210 mm
Holding pressure:	2 -4 bar
Test pressure:	4 -6 bar
Design life:	2 years
Plug weight, submerged:	Appr. 50 kg
Plug weight, dry:	Appr. 60 kg
Plug material:	Carbon steel
Sealing material:	PU
Plug sealing:	Compression packers
Plug physical support:	Friction packer
Corrosion protection:	Subsea coating and sacrificial anode
Check valve:	2 off 2" valves, 316 material
ROV operated ball valve:	2 off 2" valves, 316 material
Plug setting:	Setting bolt activated by hydraulic setting tool

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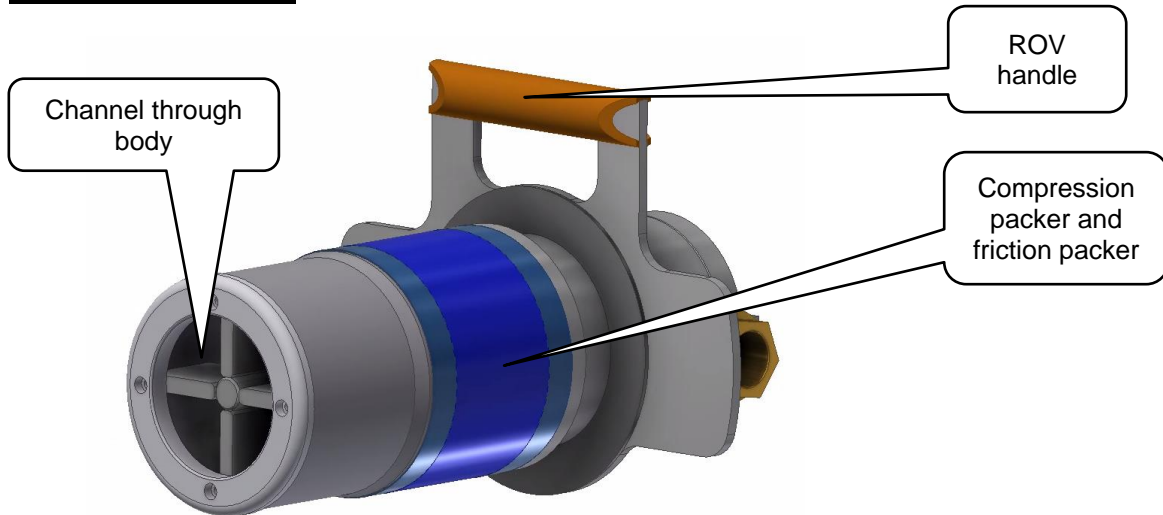
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SWIFT : DNBANKKXXX



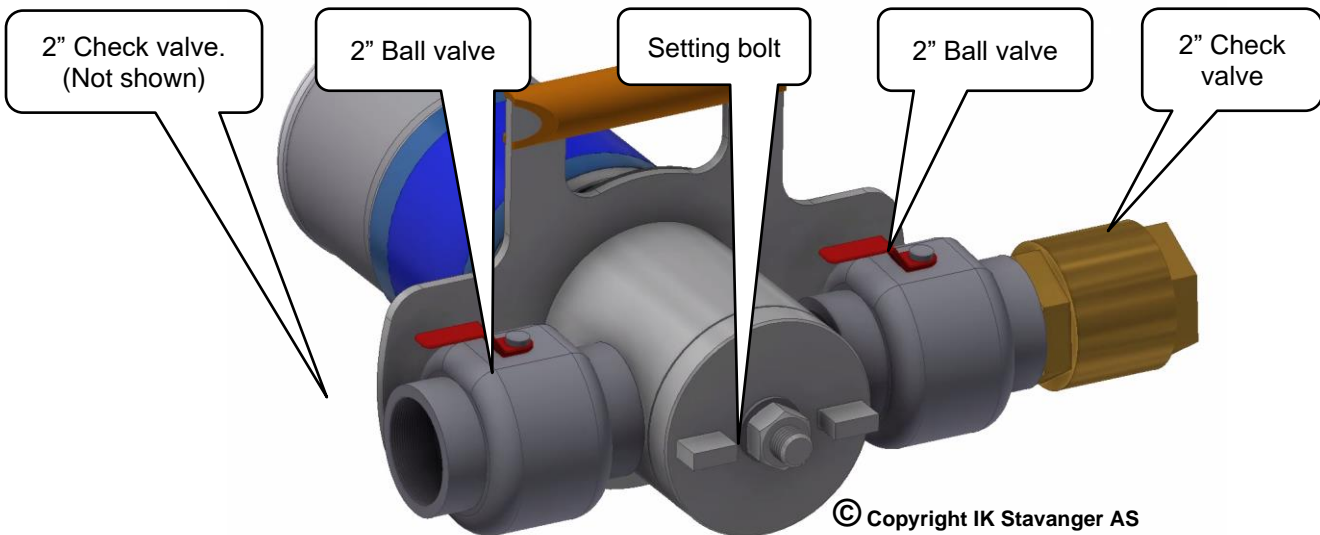


## Illustrations / Details



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*The inside of the plug layout design.*



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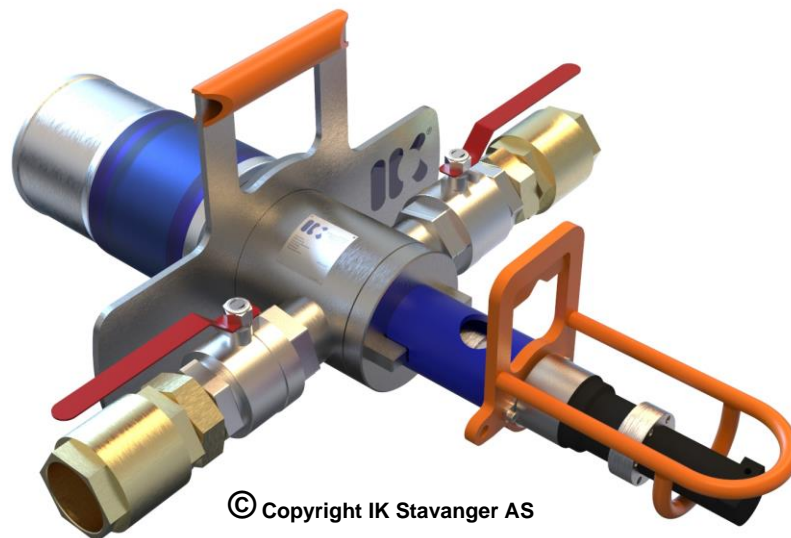
*The flushing plug with the double set of 2" ports with valves for securing of high flow.  
NB! Check valve will be installed on both ports and the valves will be equipped with an ROV interface*

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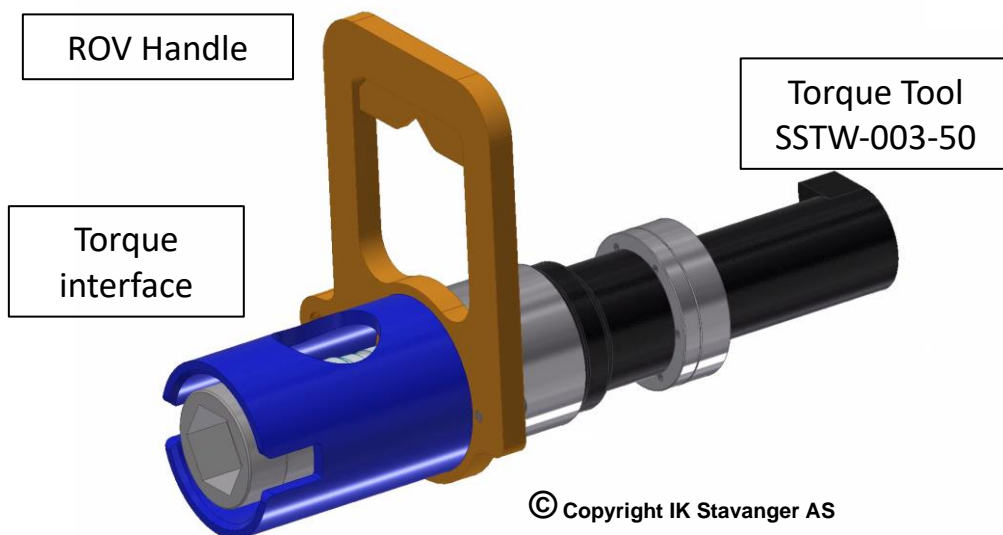
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*The plug with the double set of 2" check valves / ball valves and the setting tool connected*



*The torque tool with main parts*

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## Operational Description – Subsea Installation

1. The plug is checked and prepared for the operation and then lowered down to the WROV / installation site.
2. The plug is maneuvered / carried to the installation location by the WROV.
3. The plug is stabbed into the open pipe end.
4. When the plug is confirmed completely inserted, the torque tool is inserted.
5. The plug is set by activation through the hydraulic supply line
6. The Hydraulic pressure to be kept for a few minutes.
7. The torque tool is released and recovered to surface.

## Testing and Documentation

The plug integrity is documented by structural calculations and testing in the test rig.

In general, this plug will be low loaded.

The plug lifetime, integrity and functionality will be documented in the MRB, FAT and the Design report.



*Typical test set up example – Pipe spool with a plug in the end*

---

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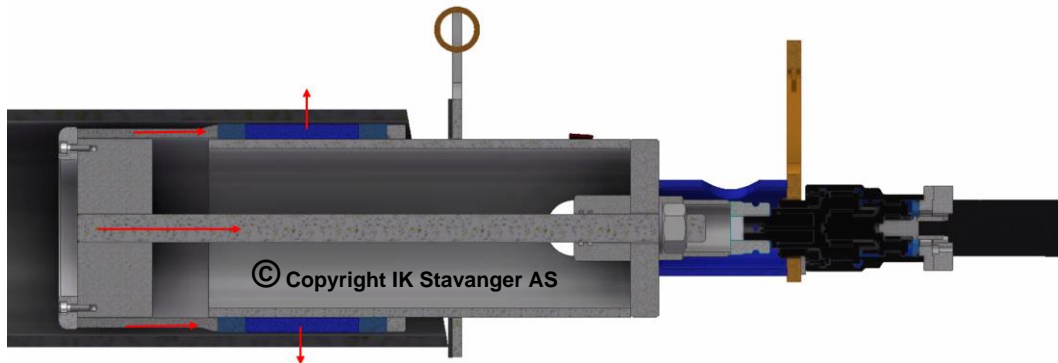
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## Technical functionality and risk considerations

The subsea compression plug is a field proven, reliable and robust tool. IK have designed and delivered several plugs over the years and have a significant track record, see Appendix B.

### Functionality



*The compression packer is expanding from the tensioning of the setting bolt. The packer pressure between the flowline and the elastomer packer ( blue element ) facilitates sealing and friction / mechanical anchoring.*

### Risk Considerations

The plug body is robust and simple with few movable parts. The following functions are included for securing the operation and the 2 years lifetime:

- The OD of the plug is significant smaller than the ID of the pipeline to handle the tolerances of roundness, ID and Wt.
- The plug can be recovered and reset if required due to unforeseen issues.
- The check valve has ROV operated ball valves for securing 100% sealing after flushing operation.
- The plugs are checked with a complete FAT confirming both the operation and the function.
- The hydraulic setting tool is proposed delivered with a backup tool for contingency

---

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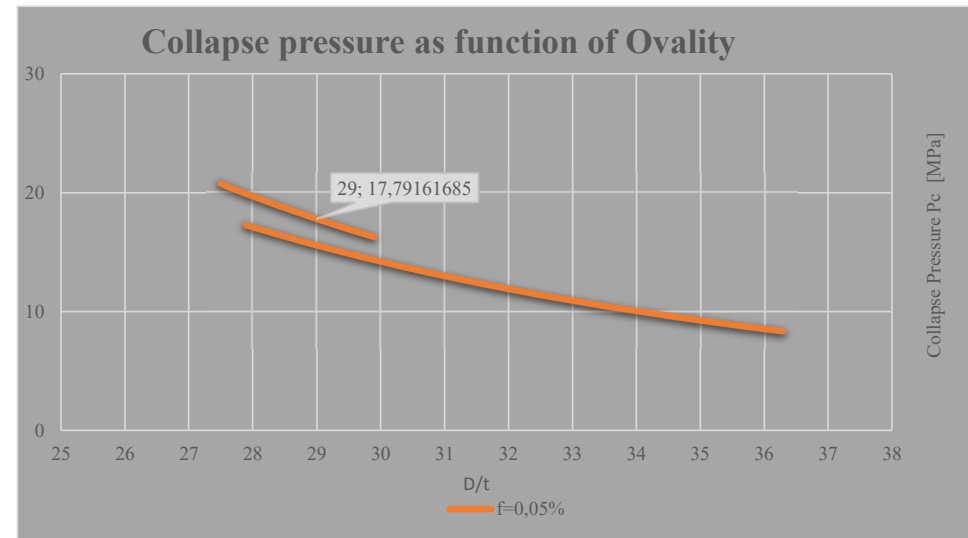
Reg.no : NO.945914777MVA P 5 of 5  
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APPENDIX C: Calculation of collapse pressure

Calculate the collapse pressure as function of D/t, ovality and fabrication factor

		Range		step
		low	high	
Diameter to Thickness ratio	D/t	27	30	0,1
Ovality	f [%]	0,05	0,1	0,1
Alpha fab		0,93		
Yield stress	fy	413	MPa	
Elastic modulus	E	201000	MPa	207000
Poissons ratio	v	0,3		

Use JIP equation                      no                      yes                      Only for D/t below 15



	SMYS	SMYS*alpha_u
X65	448	430,08
X70	482	462,72
X80	551	528,96

D/t	Ovality[%]														
	f=0,05%	f=0,15%	5,00 %	f=0,35%	f=0,45%	f=0,55%	f=0,65%	f=0,75%	f=0,85%	f=0,95%	f=1,05%	f=1,15%	f=1,25%	f=1,35%	f=1,45%
27	21,87396	21,76502	21,06954	20,46799	19,93368	19,45061	19,0083	18,59942	18,2186	17,8618	17,52585	17,20822	16,90686	16,62007	16,34644
27,1	21,64524	21,54579	20,8639	20,27256	19,74645	19,27025	18,83386	18,43019	18,05404	17,70146	17,36937	17,05531	16,75726	16,47357	16,20284
27,2	21,41918	21,32892	20,66032	20,07904	19,56102	19,09161	18,66108	18,26257	17,89104	17,54265	17,2144	16,90387	16,60911	16,32849	16,06064
27,3	21,19578	21,1144	20,45882	19,88742	19,37738	18,91468	18,48995	18,09655	17,72961	17,38537	17,06092	16,7539	16,4624	16,18483	15,91984
27,4	20,97504	20,90225	20,25939	19,6977	19,19554	18,73947	18,32047	17,93214	17,56973	17,22961	16,90893	16,60539	16,31713	16,04257	15,78042
27,5	20,75695	20,69244	20,06202	19,50989	19,01549	18,56597	18,2	17,76932	17,4114	17,07536	16,75842	16,45833	16,17327	15,90171	15,64237
27,6	20,5415	20,48498	19,86672	19,32397	18,83722	18,39417	18,0	17,60808	17,25462	16,92261	16,60937	16,3127	16,03082	15,76223	15,50568
27,7	20,32867	20,27986	19,67348	19,13995	18,66074	18,22406	17,8	17,44842	17,09936	16,77136	16,46179	16,1685	15,88977	15,62413	15,37034
27,8	20,11846	20,07706	19,4823	18,95782	18,48602	18,05564	17,7	17,29033	16,94563	16,62159	16,31565	16,02572	15,75011	15,48739	15,23634
27,9	19,91084	19,87658	19,29316	18,77757	18,31308	17,88891	17,5	17,13381	16,79342	16,4733	16,17095	15,88435	15,61183	15,352	15,10367
28	19,7058	19,6784	19,10606	18,59919	18,14189	17,72385	17,3	16,97883	16,64271	16,32647	16,02768	15,74438	15,47492	15,21795	14,97231
28,1	19,5033	19,48251	18,921	18,42268	17,97246	17,56046	17,2	16,8254	16,49349	16,18109	15,88583	15,60579	15,33937	15,08524	14,84226
28,2	19,30334	19,28889	18,73795	18,24803	17,80477	17,39872	17,0	16,6735	16,34576	16,03716	15,74539	15,46858	15,20516	14,95384	14,71351
28,3	19,10588	19,09752	18,55691	18,07522	17,63881	17,23864	16,9	16,52312	16,19951	15,89467	15,60635	15,33273	15,07229	14,82375	14,58604
28,4	18,9109	18,9084	18,37787	17,90426	17,47458	17,08019	16,7	16,37426	16,05473	15,7536	15,4687	15,19824	14,94074	14,69496	14,45984
28,5	18,71838	18,72149	18,20081	17,73512	17,31207	16,92337	16,56311	16,2269	15,9114	15,61395	15,33242	15,06509	14,81051	14,56746	14,3349
28,6	18,52828	18,53678	18,02572	17,56779	17,15126	16,76817	16,41284	16,08104	15,76951	15,47569	15,19751	14,93328	14,68158	14,44123	14,21121
28,7	18,34059	18,35426	17,85259	17,40227	16,99214	16,61457	16,26411	15,93666	15,62906	15,33883	15,06396	14,80279	14,55394	14,31627	14,08876
28,8	18,15526	18,17389	17,68139	17,23854	16,8347	16,46258	16,11691	15,79375	15,49004	15,20336	14,93175	14,67361	14,42759	14,19256	13,96754
28,9	17,97228	17,99566	17,51212	17,07658	16,67893	16,31217	15,97123	15,6523	15,35242	15,06925	14,80087	14,54573	14,3025	14,07009	13,84754
29	17,79162	17,81955	17,34476	16,91639	16,52481	16,16333	15,82705	15,5123	15,21621	14,9365	14,67132	14,41914	14,17868	13,94885	13,72874
29,1	17,61324	17,64554	17,17929	16,75795	16,37234	16,01605	15,68436	15,37374	15,08139	14,8051	14,54308	14,29382	14,0561	13,82884	13,61114
29,2	17,43712	17,4736	17,01569	16,60125	16,22151	15,87032	15,54316	15,2366	14,94794	14,67504	14,41613	14,16978	13,93475	13,71003	13,49472
29,3	17,26323	17,30371	16,85395	16,44626	16,07228	15,72612	15,40343	15,10088	14,81586	14,5463	14,29048	14,04699	13,81464	13,59242	13,37947
29,4	17,09154	17,13585	16,69406	16,29298	15,92466	15,58345	15,26516	14,96656	14,68514	14,41887	14,1661	13,92544	13,69573	13,476	13,26538
29,5	16,92202	16,97	16,53598	16,14139	15,77864	15,4423	15,12833	14,83363	14,55576	14,29275	14,04299	13,80512	13,57803	13,36075	13,15245
29,6	16,75465	16,80614	16,37971	15,99148	15,63419	15,30263	14,99293	14,70208	14,42772	14,16792	13,92113	13,68603	13,46153	13,24667	13,04065
29,7	16,58939	16,64423	16,22523	15,84322	15,4913	15,16446	14,85896	14,5719	14,30099	14,04437	13,80051	13,56815	13,3462	13,13374	12,92998
29,8	16,42621	16,48426	16,07251	15,69661	15,34995	15,02775	14,72639	14,44307	14,17557	13,92209	13,68113	13,45147	13,23204	13,02195	12,82043
29,9	16,26509	16,32621	15,92154	15,55163	15,21014	14,8925	14,59522	14,31558	14,05145	13,80106	13,56297	13,33597	13,11904	12,9113	12,71198

```

Sub Collapse_pressure()
'Imports System.Math

' Collapse_pressure Macro
,
Dim OD As Variant
Dim t As Variant
Dim fy As Variant
Dim E As Variant
Dim nu As Variant
Dim alpha_fab As Variant
Dim A As Variant
Dim B As Variant
Dim C As Variant
Dim D As Variant
Dim PE As Variant
Dim PP As Variant
Dim PC As Variant
Dim Oval As Variant
Dim tolerance As Variant
Dim WD As Variant
Dim g_m As Variant
Dim g_sc As Variant
Dim Ratio As Variant
Dim density As Variant
,
Dim Dt As Variant
Dim rownr As Variant
Dim colnr As Variant
Dim Step_dt As Variant
Dim Step_oval As Variant
Dim Dt_low As Variant
Dim Dt_high As Variant
Dim Oval_low As Variant
Dim Oval_high As Variant
Dim new_equation As String

Dim i As Variant

Dt_low = Cells(6, 3).Value
Dt_high = Cells(6, 4).Value
Step_dt = Cells(6, 5).Value
Oval_low = Cells(7, 3).Value / 100
Oval_high = Cells(7, 4).Value / 100
Step_oval = Cells(7, 5).Value / 100
alpha_fab = Cells(8, 3).Value
fy = Cells(9, 3).Value
E = Cells(10, 3).Value
nu = Cells(11, 3).Value
new_equation = Cells(12, 3).Value
'OD = Cells(2, 2).Value
't = Cells(3, 2).Value

```

```

'g_m = Cells(9, 2).Value
'g_sc_lb = Cells(10, 2).Value

'Cells(14, 3).Value = 1
'Cells(15, 3).Value = PE
'Elastisk collapse pressure
'PE = 2 * E * (t / OD) ^ 3 / (1 - nu ^ 2)
'Plastisk collapse pressure
'PP = fy * alpha_fab * 2 * t / OD
'Cells(14, 2).Value = PE
'Cells(15, 2).Value = PP

'cells(17, 2) = PCS
'Cells(17, 3) = P_coll_anal(PP, PE, OD, t, Oval)
'-----
'Collapse pressure including safety factors
'PC_d = PC_i / (g_m * g_sc_lb)
' Cells(18, 2) = PC_d
'ratio collapse pressure to external pressure including safety factors
'Ratio = PC_d / Pext
'Cells(19, 2).Value = Ratio
tolerance = 0.001
Cells(19, 2) = "D/t"
Cells(20, 2) = Dt_low
Dt = Dt_low
'startlinje for skriving av data
rownr = 20
Oval = Oval_low

Cells(19, 5) = Oval * 100
'----- starter utregningsløkke ---
Do Until Dt > Dt_high
  Cells(rownr, 2) = Dt
'startkolonne for utregning av data
colnr = 3
'
  Do Until Oval > Oval_high
    If rownr = 20 Then
      'skriver bare ovaliteten 1 gang i toppen
      Cells(19, colnr) = "f=" + CStr(Oval * 100) + "%"
    End If
'sjekker om ny formel fra JIP skal brukes eller standard
If new_equation = "yes" Then
  If Dt < 20 Then
    Cells(rownr, colnr) = P_coll_anal(E, fy, nu, alpha_fab, Dt, Oval) * (1.2 - 0.01 * Dt)
  Else
    Cells(rownr, colnr) = P_coll_anal(E, fy, nu, alpha_fab, Dt, Oval)
  End If
Else
  Cells(rownr, colnr) = P_coll_anal(E, fy, nu, alpha_fab, Dt, Oval)
End If

  Oval = Oval + Step_oval
  colnr = colnr + 1

Loop

```



```

Dt = Dt + Step_dt
rownr = rownr + 1
Oval = Oval_low
Loop

```

End Sub

---

```

Function P_coll_anal(E, fy, nu, alpha_fab, Dt, Oval As Variant) As Double
'Elastisk collapse pressure
PE = 2 * E * 1 / Dt ^ 3 / (1 - nu ^ 2)
'Plastisk collapse pressure
PP = fy * alpha_fab * 2 * 1 / Dt
B_s = -PE
C_1_s = -PP ^ 2 - Oval * PE * Dt * PP
D_s = PE * PP ^ 2
US = 1 / 3 * (-B_s ^ 2 / 3 + C_1_s)
VS = 1 / 2 * (2 / 27 * B_s ^ 3 - 1 / 3 * B_s * C_1_s + D_s)
'test = (-US ^ 3) ^ 1 / 2
PhiS = Application.Acos(-VS / (-US ^ 3) ^ 0.5)
YS = -2 * (-US) ^ 0.5 * Cos(1 / 3 * Application.Pi() + PhiS / 3)
PCS = YS - 1 / 3 * B_s

P_coll_anal = PCS
End Function

```

---

```

Function P_collapse(E, fy, nu, alpha_fab, Dt, Oval, tolerance As Variant) As Double
'this function is iterating by using Newtons method to find the solution
'polynom faktorerer
'Elastisk collapse pressure
PE = 2 * E * 1 / Dt ^ 3 / (1 - nu ^ 2)
,
'Plastisk collapse pressure
PP = fy * alpha_fab * 2 * 1 / Dt
,
D = PP ^ 2 * PE
' C = -PP ^ 2 - Oval * PE * OD / t * PP
C = -PP ^ 2 - Oval * PE * Dt * PP
B = -PE
A = 1

i = 0

PC = PP
'If PP > PE Then
'PC = PP
' Else
' PC = PE
' End If
'PC = 116.9805302

Do Until Abs(PC_i - PC) <= tolerance

```

```

poly = PC ^ 3 + B * PC ^ 2 + C * PC + D

deri = (3 * A * PC ^ 2 + 2 * B * PC + C)
brok = poly / deri
PC_i = PC - brok
'PC_i = PC - (A * PC ^ 3 + B * PC ^ 2 + C * PC + D) / (3 * A * PC ^ 2 + 2 * B * PC + C)
'If PC_i > PE Then ' feil løsning
'If PC_i < 0 Then
'PC_i = PP
'End If
tt = Abs(PC_i - PC)
i = i + 1
PC = PC_i
Loop

P_collapse = PC_i

```

End Function

---

```

Function P_c_anal(PP, PE, OD, t, Oval As Variant) As Double
B_s = -PE
C_1_s = -PP ^ 2 - Oval * PE * OD / t * PP
D_s = PE * PP ^ 2
US = 1 / 3 * (-B_s ^ 2 / 3 + C_1_s)
VS = 1 / 2 * (2 / 27 * B_s ^ 3 - 1 / 3 * B_s * C_1_s + D_s)
test = (-US ^ 3) ^ 1 / 2
PhiS = Application.Acos(-VS / (-US ^ 3) ^ 0.5)
YS = -2 * (-US) ^ 0.5 * Cos(1 / 3 * Application.Pi() + PhiS / 3)
PCS = YS - 1 / 3 * B_s

P_coll_anal = PCS
End Function

```