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Ja, Gassco

Ensuring contaminate free gas delivery

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Bachelor's thesis in Mechanical Engineering

Haugesund, Norway 2022

Høgskulen på Vestlandet

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Preface

This bachelor thesis was written at the Department of Mechanical and Marine Engineering at Western University of Applied Sciences (WNUAS) in Mechanical Engineering, Process and energy technology. The field of study made Gassco a very suitable choice as sponsor. After meetings with the roles involved, an issue based on knowledge from Process subjects was worked out.

The purpose of the issue was not only to find a correct solution, but also to incorporate knowledge from different studies and research information found about ensuring a gas free from contaminants.

The ambition of this thesis is to give the reader an introduction to different ways on how to transport a gas free of contaminants. The main focus are principles and concepts, rather than engineering a brand-new product. It also explains how and why the group came up with the solution given.

We would like to thank our sponsor Gassco for the opportunity to write this thesis with them. Also a big thank you to our external supervisor from Gassco Vidar R. Nilsen, and the internal supervisors from Høgskulen på Vestlandet (HVL) Jorunn Stueland Nysted and Ståle Bright Pettersen.

Date and place:

Haugesund 30.05.2022

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Abstract

This thesis deals with investigations and proposals on how to ensure contaminant free gas delivery. It is a concept study where emphasis is on the results and discussion chapter. A large part of the assignment is background investigations, obtaining information and thoroughly analysing the subject matter. The goal of the thesis is to find alternatives which eliminate the root cause or remove the problem of black powder sometimes found in a sales gas post-pigging. This so it can be delivered according to specifications and prevent larger amounts of black powder from accumulating in the receiving terminal and affect operations. Gassco's vision with this bachelor thesis was for the group to think innovatively and "outside the box" so that new untested ideas could emerge.

The group has done background research on the main sources of contaminants; corrosion and black powder. In order to develop proposals to eliminate or mitigate contaminants from occurring within the flow, a greater understanding of the origin of the issue is essential. The thesis builds around the case of transportation of natural gas from offshore to a confidential receiving terminal in Europe. Theory and technical information have been researched thoroughly in order to gain necessary background information and increase technical competence enabling the development of the solutions presented in chapter 4: Results.

The issue the thesis investigates arises after the natural gas has been transferred from the platform into the pipeline. Therefore, the thesis elaborates on the issues of pipe maintenance, the sources of corrosion and how corrosion can occur. These are important aspects to understand in order to be able to suggest a solution to the problem.

The proposed solutions are divided into two main groups:

- Suggestions on how to eliminate the black powder problem
- Suggestions on how to mitigate already formed black powder

The solutions presented in this thesis have been proposed, discussed and then either rejected or deemed as feasible. At the request of our sponsor Gassco, all suggested ideas are included in the thesis, both the rejected and those that are considered feasible.

The group worked out the following conclusion: recommend replacing the existing cyclone separator with cyclone filter to get a more efficient gas purification. It is also suggested to thoroughly analyse the black powder to gain more information, as well as changing the pigging equipment to one better suited for removal of black powder. Implementation of these suggestions will ensure gas delivery to specifications at all times, with regards to contaminants.

Sammendrag

Denne oppgaven omhandler undersøkelser og forslag til hvordan en kan sikre forurensningsfri gass leveranse, og er en konseptstudie hvor det legges stor vekt på resultat og diskusjons kapittelet. En stor del av oppgaven er bakgrunns undersøkelser og innhenting av fagstoff som analyseres grundig. Målet med oppgaven er å finne alternativer som eliminerer rot årsaken, eller fjerner problemet med svart støv i salgs gass. Dette slik at gassen kan leveres i henhold til spesifikasjoner, hindre at større mengder svart støv akkumuleres i mottaks terminalen og tetter rør med tilhørende instrumentering. Gasscos visjon med bacheloroppgaven var at gruppen skulle tenke innovativt og «utenfor boksen» slik at det kunne dukke opp nye uprøvde ideer.

Gruppen har utført bakgrunns undersøkelser om hovedkildene til korrosjon og svart støv, dette for å få en større forståelse rundt opprinnelsen til svart støv. Oppgaven bygger opp rundt gassens transport fra offshore frem til mottaks terminal i Europa. Teori og teknisk informasjon er undersøkt for å opparbeide bakgrunns informasjon og øke den tekniske kompetansen for å kunne foreslå løsningene som legges frem i kapittel 4 resultater.

Problemstillingen denne oppgaven skal undersøke, oppstår etter at naturgassen er transportert fra plattformen til rørledningen. Denne oppgaven går derfor i dybden på vedlikehold av rør, hva som er kildene til korrosjon og hvordan korrosjon kan oppstå. Dette er viktige elementer å undersøke hvis det skal være mulig å foreslå en løsning til problemet.

Oppgaven er delt opp i to hovedgrupper når det kommer til løsninger:

- Forslag til hvordan en eliminerer kilden til svart støv problemet
- Forslag til hvordan en minimerer allerede oppstått svart støv

Løsningene i oppgaven er blitt foreslått, diskutert og deretter anbefalt eller avslått. Etter ønske fra Gassco er alle utarbeidet ideer tatt med i oppgaven, både de avviste og de som anses som gjennomførbare. Svart støv er også nøye beskrevet.

Gruppen er kommet frem til følgende konklusjon: det anbefales å bytte ut eksisterende syklon separator med syklon filter for å få en mer effektiv gassrensing. Det ønskes også å ta grundige undersøkelser av det svarte støvet, samt endre piggeprogram til et med pigger som er bedre egnet for fjerning av svart støv. Dette for å sikre forurensningsfri gassleveranse.

Table of content

Dictionary

Word	Description
BCM	Billion standard Cubic Meters
Black powder	Corrosion powder in gas pipelines
Black mud	Wet black powder
Bi-Di pig	Bi-directional pig
Dry gas	Dehydrated natural gas
EU	European Union
Hydrates	Mixed natural gas and water, create a crystalline structure
ISO	International Standard Organization
Mercaptans	Other sulphur components
Methodology	Study of research methods
Metered	Measuring the gas flow
NAS	National Aerospace Standard
Norsok standard	The Norwegian shelf's competitive position
OED	Oil and Energy Department
PFD	Process flow diagram
Pig	A tool inserted into the pipeline for maintenance operations
Pollutant	A substance that pollutes something
P&ID	Piping and instrumentation diagram
TSP	Technical Service Provider
Vapor	Gas phase at a temperature lower than its critical temperature.
Well stream	Stream from the reservoir to the platform

1. Introduction

Figure 1: Gassco logo from Gassco webpage [1]

Gassco is an operator for the integrated processing and exportation systems for natural gas produced within the Norwegian continental shelf and sold to the European market. The company logo is shown in Figure 1. This role confers overall responsibility for operating the infrastructure on behalf of the owners of the infrastructure. The company is fully owned by the Norwegian government and was established by the Oil and Energy Department (OED) May 14th in 2001, conforming to established EU regulations.

As an operator for a diversity of interest composed of different ownerships, Gassco has the holistic responsibility for operation and development of the infrastructure on the Norwegian Continental Shelf and to Europe. This also includes the responsibility for safe and efficient transport of gas through the 8000km of pipelines, currently transporting more than 100 BCM annually. Gassco's headquarter is in Karmøy, which is an island on the west coast of Norway. Gassco is currently the operator for three processing plants along the Norwegian coastline: Kårstø, Kollnes, and Nyhamna.

1.1 Background for the issue

To ensure maintained integrity of pipelines, there are requirements, procedures and regulations to inspect the pipelines at regular intervals. The interval for this inspection is typically once every 10 years per pipeline[1], and the inspection is done in an operation called pigging, (more about this in chapter 3.7). Based on the long-term experience by the operator, the contaminants addressed in this thesis will mainly come from two sources; dust generated from pigging operations (primary source) and compressor oils from upstream compressors (secondary source). The origin of the thesis is based on past experience with pigging operations. From these pigging operations, contaminants have been uncovered in the downstream gas delivery system, where the majority of it was fine grained black powder. Based upon this, the contaminant this thesis will primarily focus on will be black powder, an intermittent problem, (see chapter 3.6 for more details).

[1] Information from Vidar R. Nilsen at Gassco

The issue has been the subject of several early phase studies in Gassco, and several concepts have been proposed. The only study to mature a concept, was however more costly than anticipated and had challenging installation. Based on this, the thesis was presented to get fresh eyes on the issue so that other innovative ideas might present itself.

1.2 Presenting the issue

The thesis will take a deeper look into the issue with black powder within the downstream system of processing plants. The objective of the thesis is to study alternatives which will adequately mitigate or eliminate black powder from a sales gas stream in order to:

1. Continue to achieve the export specification according to the customer requirements.
2. Prevent significant quantities of black powder accumulating in the receiving terminal, causing wear and clogging of piping and equipment.

The object of this thesis is a gas receiving terminal in continental Europe. Since the start up, the terminal has been equipped with cyclone separators as the only means of cleaning the incoming gas for solid and liquid trace components. Operational experience and inspections over time indicate that there may have been some minor internal corrosion/reaction in the process, thought to be caused by minor amounts of oils in the gas stream believed to stem from upstream compressors. This internal corrosion indicate that the upstream cyclone separators do not adequately remove contaminants during normal operation. At the behest of the sponsor, the liquids issue will be disregarded in this thesis.

Additionally, it has been observed that the upstream cyclones do not prevent the fouling of downstream equipment with black powder particles following pigging operations. This thesis is a concept study and focuses on research with alternatives on how to mitigate, or eliminate, the occurrence of black powder after pigging.

2. Method

The objective of the thesis was to study alternatives which will adequately remove black powder from gas stream to continue to achieve the export specification to the customer and prevent significant quantities of solid contaminants depositing in the process piping and equipment. The primary task of this thesis is to brainstorm innovative and potentially lower cost alternatives than the ones previously studied, with a focus on looking at alternatives which represented an adequate solution to the issue.

2.1 Concept study as a method

It was requested to focus on concepts rather than specific engineering solutions. Conceptual research is defined as a methodology wherein research is conducted by observing and analysing already presented information on a given topic. Conceptual research does not involve conducting any practical experiments or mathematical confirmations. It is related to abstract concepts or ideas [42].

To find the information needed, qualitative research has been performed, where document analysis was the main method, after gathering information. When the alternatives were discovered, they were assessed versus each other to be able to define the solution. Secondary data was obtained in form of scientific books, articles and reports. After analysing the secondary data, the primary data from the researchers was put in the thesis.

2.1.1 Document analysis

As mentioned, document analysis is a form of qualitative research. Analysing documents and answering specific research questions was a big part of the prewriting process. Like other methods of analysis in qualitative research, document analysis requires repeated review, examination, and interpretation of the data to gain meaning and empirical knowledge of the case being studied.

It is important to note that qualitative research requires robust data collection techniques and the documentation of the research procedure. Burns and Grove defines qualitative research: "It is a systematic, subjective approach used to describe phenomena and give them meaning and focuses on understanding within the holistic framework. It provides richness, depth and complexity in describing the aspect of interest" [10].

2.1.2 Obstacles

Concept studies with document analysis as a methodology is a less controlled and more interpretive way of research. "It requires self-prejudicial appraisal as an admission that research can be influenced by the researcher. Qualitative research is an emphatic experience and a self-reflective journey" [11]. There was a need to reflect on the position as researchers, considering how participation and perception might have influenced the results. A known fact with the chosen methodology is that it may give a subjective conclusion as a result of the authors own interpretation of the research done.

3. Theoretical background information

3.1 Natural gas

Natural gas is a term for fossil energy source that formed deep beneath the earth´s surface. Natural gas contains many different compounds in various amounts. The largest fraction is methane (CH_4). I It also contains fractions of Ethane, Propane and Butanes and small and diminishing quantities of heavier hydrocarbons. In addition, it also contains nonhydrocarbon gases, such as carbon dioxide, nitrogen and water vapor [28].

The natural gas is transported from the reservoir to the surface through a well pipe. When the well stream reaches the surface, it appears in three phases: oil, gas and produced water. These three phases should be separated from each other for ease of exportation. These phases will separate on its own over time in distinguished layers because of different densities. A typical method for separating these phases is based on residence time in a large tank, technically termed *a* separator*.* The separator has separate compartments for separating, storing and exporting the different phases. Gas has the lowest density and will therefore rise to the top and exit the separator at a top located nozzle [41]. It will then be treated through cooling and re-heating to remove residing water vapor and other unwanted components. This is done to achieve the target specification and get marketable gas and prevent the risk of forming hydrates in the export pipeline. Drying is one of the essential precautions that should be done to moderate the localized corrosion [32].

Table 1 shows a typical example of the composition of the natural gas flowing in the thesis pipeline. This composition varies depending on the routing of gas and changing composition from wells over time.

Table 1: Composition of natural gas [2]

Composition natural gas		
[C1] Methane	Mol %	91.59
[C2] Etan	Mol %	4.41
[C3] Propane	Mol %	0.92
[C4] Butane	Mol %	0.28
[NC4] Normal Butane	Mol %	0.13
[IC5] Iso Pentane	Mol %	0.06
[NC5] Normal Pentane	Mol %	0.03
[C6+]	Mol %	0.07
[N2] Nitrogen	Mol %	1.30
[CO2] Carbondioxid	Mol %	1.21
Sum		100.00
[H2S] Hydrogen sulphide	mg/Nm^3	5

3.2 Pipelines

Natural gas pipelines are used for the transportation of natural gas produced from gas fields, either onshore or offshore facilities, to commercial, residential, industrial, and utility companies. A pipeline can consist of pumps, valves, and control devices for conveying liquids, gases, or finely divided solids. Figure 2 show the infrastructure of Gassco operated gas pipelines.

The pipeline of concern in this thesis is a 40-inch pipeline, stretching about 800 km along the seabed, transporting marketable gas from offshore all the way to the receiving terminal onshore. This pipeline has been carefully designed to be able to achieve certain goals; to last for decades, be flow operable/manageable and to be maintained with pigs being sent through it. To achieve set goals, the following points has been included in the design [2]:

- Internal coating for corrosive resistance and more
- Full bore valves to operate the flow in a desired way (made full bore in order to be pig able)
- Using 5D bends (stretching 5 x nominal diameter to turn 90 degrees) to be certain that pigs will not get stuck.

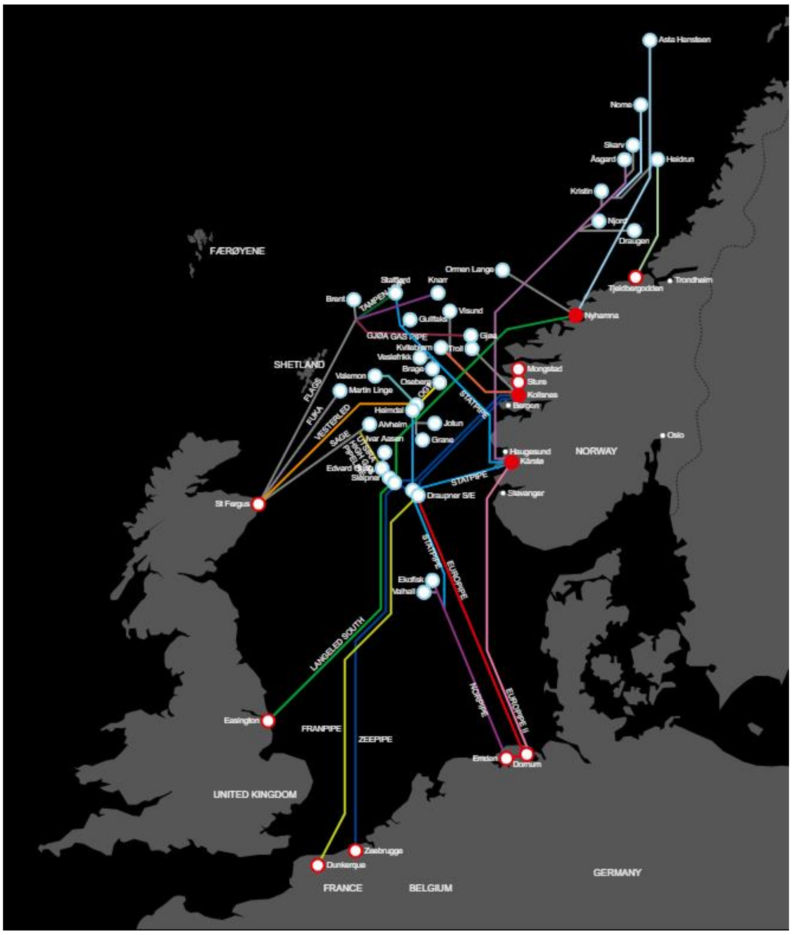

Figure 2: Map of pipeline infrastructure[1]

3.3 Receiving terminals

Natural gas is transported to receiving terminals from offshore/onshore installations. These terminals can have a variety of purposes; some are for gas storage, some for processing and others are only for importing/exporting natural gas. The gas is purified and temperature regulated to be fiscally metered prior to being transported into the downstream system for distribution.

Figure 3 show a receiving terminal in continental Europe.

Figure 3: Gas receiving terminal [2]

3.3.1 Thesis terminal

Due to confidentiality restrictions, the exact location can't be shared openly, so a brief overview of the essential data is what will be shared in this thesis. The terminal is located in continental Europe. It has been operational for 30 years. The terminal is near crucial gas markets in Europe and is linked by a 40-inch pipeline to the offshore hub. The terminal itself receives exported gas from the Norwegian continental shelf through an intricate pipeline system along the seabed. The gas is processed (via temperature and pressure regulation and possible residual water, liquids and solids removal), metered, quality checked and then transported further into the European continent. Figure 4 shows a brief overview of the receiving gas terminal. For more information about the thesis terminal see the Process Flow Diagram Attachment 1, PFD thesis terminal

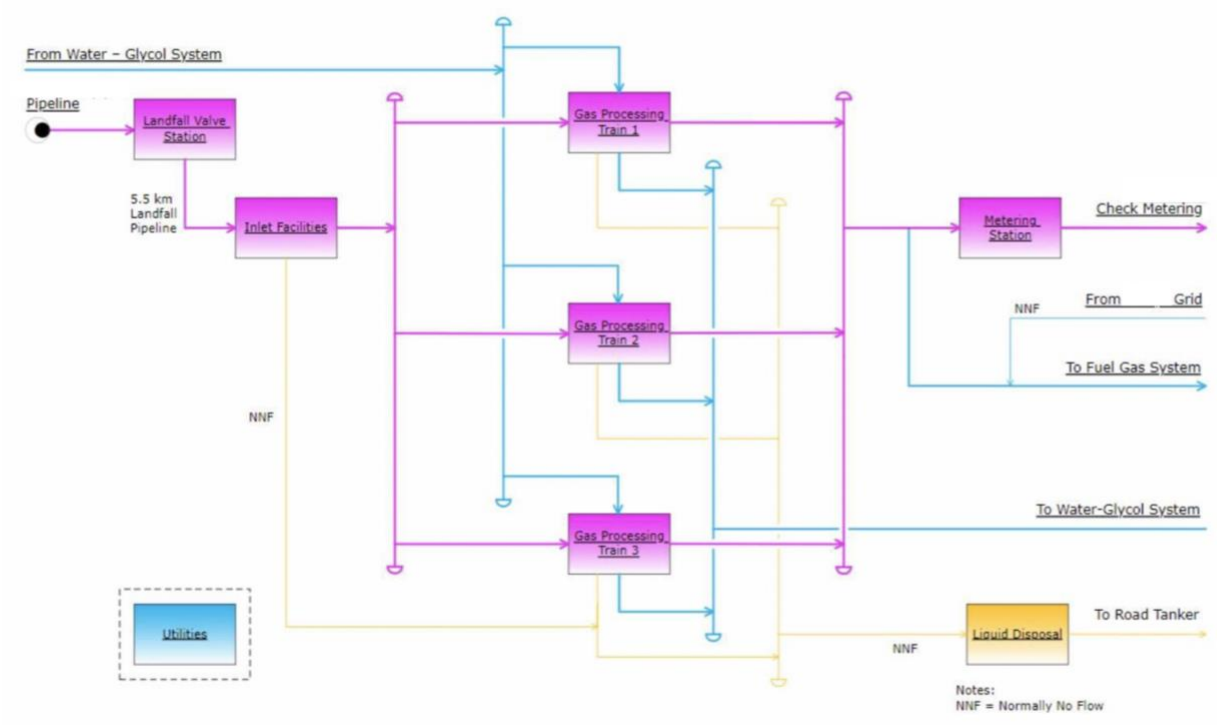

Figure 4: Typical Block Flow Diagram of gas receiving terminal [2]

The sold natural gas is expected to be free of unpleasant odours, materials, liquids, waxes and chewing gum-forming constituents and free of dust or other solids. These may cause damage to or interfere with the proper operation of the transportation system. Table 2 shows several pressure and temperature conditions from arrival and through the terminal, with reference to the terminal's basic training manual.

Table 2 shows the dry gas specification of the receiving terminal.

Table 2: Dry gas specifications [2]

Gas parameter requirements for the receiving terminal onshore	
Maximum design pressure	≈ 150 barg[2]
Maximum design temperature	50 °C
Minimum design temperature	-10 °C
Total capacity	(*[3]) MSm^3 /d 3 x 50% configuration
Hydrocarbon dewpoint (at 50barg)	< -10 °C
Water dew point (at 69barg)	-18 °C
Maximum carbon dioxide	2,50 mole%
Maximum oxygen	2 ppm
Maximum hydrogen sulphide	5 mg/Nm^3
Maximum sulphur	30 mg/Nm^3
Maximum mercaptans	6 mg/Nm^3
Typical operation values	
Pressure	75-100barg
Temperature	2-14 °C Depending on the season

The function of the Terminal is to condition gas received from the offshore pipeline for distribution into the downstream operator's transmission system. To meet the specification, the flow, pressure and temperature of the sales gas are checked; the temperature is normally kept at minimum 2°C. The properties of the delivered sales gas will depend on the current mixing conditions in the upstream system.

[2] Exact design pressure is confidential information

[3] Total capacity is confidential information

3.4 Gas purification

Gas purification is a method of removing pollutants, such as other gases, solid particles or droplets from the gas. Gas purification is mostly used to reduce emissions of air pollutants into the atmosphere or in chemical and metallurgical industrial processes [27]. It is also used in the production of pure gases for technical use. The following are two common ways to purify gas and are relevant for this thesis.

3.4.1 Cyclone separator

Figure 5: Existing cyclone separator [2]

There are many different devices used for gas contaminants control, cyclone separators shown in Figure 5 are one of them. They are usually only referred to as cyclones, which are separation devices. A cyclone is used to remove unwanted solid or liquid materials from industrial fluids. It works by spinning objects around a centre axis. This spinning pushes harder on dense material than on less dense material due to mass moment of inertia, separating objects by their densities. A separator has a continuous feed of gas fed into a chamber, where a spiralling vortex is generated. Components with less inertia, which are the lighter ones, are more easily influenced by the vortex and travel up. On the contrary larger components of pollution have more inertia and have difficulty following the high-speed spiral motion of the gas and vortex. These particles hit inside the container walls and drop down into a collection bin. The chamber is shaped like an upside-down cone, to collect the particles at the bottom and let the cleaned gas escape out of the top. Most cyclones are built to control and remove larger particles and liquids, this makes them seen as a coarse separator. A common name for them is pre-cleaners, since they remove larger pieces of particulate matter before finer filtration is done [3].

Generally, a cyclone is able to remove from 55% to 99% of all particulate matter in the gas [3]. It all depends on the size-distribution of the particles. Lighter particles are harder to separate out, making a cyclone work better on gas containing large amount of heavier particles. Like other devices there are both advantages and disadvantages in using a cyclone separator.

They are beneficial because:

- They have no moving parts, and are easy to install and maintain, making maintenance and operating costs lower.
- Removed particles are easy to dispose of since they are collected when dry
- The unit takes up relatively little space

The disadvantages are mainly an inability to collect the smallest particles less than 10 micrometres [3] and it cannot handle sticky or tacky materials well.

3.4.2 Filter

A filter is a porous substance used in chemistry to segregate particles of variable sizes from liquids or gases [24]. Some examples of such substances are sand, burnt kaolin and asbestos fibre, as well as cloth of cotton, glass or plastic fibre. They are available for filtering fluids, as well as electrical and optical phenomena [25].

Gas filters are used in systems that require particulate-free gas. A gas filter system usually consists of a filter element and the housing containing the element. They come in shapes for specific applications such as cleanrooms, range hoods, furnaces or automobile engines. A filter can remove a variety of contaminants including fumes, dust, bacteria, and oils.

When choosing the necessary filter element, the particle size must be taken into consideration. There are two standards that’s possible to follow in order to define cleanliness of a fluid: National Aerospace Standard (NAS) 1636 or International Standard Organization (ISO) 4406, where NAS has been regularly used in oil and gas industry. The contamination classes (NAS) are defined by a number from 00-12. These numbers indicate the maximum number of particles per 100mL, counted on a differential basis in given size bracket the filter would let through. The filter needs to get rid of as much of the contaminates as possible within the specified range brackets, according to the established cleanliness requirement (NAS number/code). Table 3 shows the maximum contamination limits and is used to choose the necessary filter element.Table 3: Shows the NAS values to choose filter element [4]

Table 3: Shows the NAS values to choose filter element [4]

Maximum Contamination Limits (per 100 mL)						
		Size range in microns				
Approximate ISO 4406 Equivalent	NAS 1638 code	5-15 µm	15-25 µm	25-50 µm	50-100 µm	Over 100 µm
—	00	125	22	4	1	0
—	0	250	44	8	2	0
12/10/7	1	500	89	16	3	1
13/11/8	2	1000	178	32	6	1
14/12/9	3	2000	356	63	11	2
15/13/10	4	4000	712	126	22	4
16/14/11	5	8000	1425	253	45	8
17/15/12	6	16,000	2850	506	90	16
18/16/13	7	32,000	5700	1012	190	32
19/17/14	8	64,000	11,400	2025	360	64
20/18/15	9	128,000	22,800	4050	720	128
21/19/16	10	256,000	45,600	8100	1440	256
22/20/17	11	512,000	91,200	16,200	2880	512
23/21/18	12	1,024,000	182,400	32,400	5760	1020

3.5 Corrosion

Corrosion is defined as the degradation of metals. It is a natural process that converts a refined metal into a more chemically stable form such as oxide, hydroxide, carbonate, or sulphide. It is the gradual destruction of materials, ordinarily beginning at the surface. Corrosion of the metals and nonmetals takes place due to the gradual environmental interaction on the material surface. This is done by a chemical or electrochemical reaction with their environment. The biggest challenge with corrosion is the economic costs associated with it. "It has been estimated that approximately 5% of an industrialized nation´s income is spent on corrosion prevention and the maintenance or replacement of lost or contaminated as a result of corrosion reactions" [12] . In metals there is actual material loss either by dissolution (corrosion) or by the formation of non-metallic scale or film (oxidation).

3.5.1 Forms of corrosion

Corrosion appears in many forms. It is convenient to introduce the main forms of corrosion to understand those which are important for this thesis. Corrosion is usually classified into seven forms: uniform, galvanic, crevice, selective leaching, stress corrosion, erosion corrosion and pitting [12]. Corrosion content is collected from the book of Materials Science and Engineering [12].

Uniform

General corrosion is another name for uniform corrosion, is the uniform loss of metal over an entire surface. This type of corrosion may be the most common form; however, it is not the most serious form since it is easy to predict. Uniform attack is a form of electrochemical corrosion.

Galvanic

Galvanic corrosion is a form of electrochemical corrosion (see chapter 3.5.2), and it occurs between two different metals that are connected and plunged into a conductive solution. The more inert metal is protected (cathode), whilst the less noble metal will experience corrosion (anode). This form of corrosion is often used to protect maritime equipment.

Crevice

Electrochemical corrosion may also appear in crevices, for example between two riveted sheets or in bolted joints. When dust, sand and other corrosive substances are deposited on surfaces, they create an environment where water will accumulate and corrode the part.

Selective Leaching

Selective leaching is a corrosion type in some solid solution alloys, when in suitable conditions a component of the alloys is preferentially leached from the material. The most common example is the dezincification of brass, in which zinc is selectively leached from a copper–zinc brass alloy.

Stress corrosion

Stress corrosion results when a material exists in a relatively inert environment but corrodes due to an applied stress; both influences are necessary for this form of corrosion to take place. This form of corrosion is particularly dangerous. It may not occur under a particular set of conditions until there is an applied stress, and it's also not clearly visible prior to fracture and can result in catastrophic failure.

Pitting

Pitting is another form of very localized corrosion attack in which small pits or holes form. They ordinarily penetrate from the top of a horizontal surface downward in a nearly vertical direction. Pitting corrosion is a localized form of corrosion by which cavities or holes are produced in the material. It is most common to occur where there is destroyed or no coating. This creates a weak point where water or corrosive solutions attack the area. This form of corrosion is often seen inside oil and gas pipelines.

Erosion corrosion

Virtually all metal alloys, to one degree or another, are susceptible to erosion corrosion. Erosion corrosion is the combined effect that occurs due to corrosion and erosion and is caused by the rapid flow of any turbulent fluid on a metal surface. The rate of erosion increases in turbulent conditions therefore erosion is commonly found in piping at bends, elbows, and abrupt changes in pipe diameter; positions where the fluid changes direction or flow rate and suddenly becomes more turbulent.

3.5.2 Corrosion in gas pipeline

The primary chemical components that cause corrosion reaction to occur in natural gas pipelines are, oxygen (O_2), water (H_2O), hydrogen sulphide (H_2S) and carbon dioxide (CO_2). These are all components which can dissolve in the water within the pipeline. Corrosion of most pipelines occurs due to an electrochemical reaction in the presence of an electrolyte. When dissolved in aqueous solutions, acid gases such as CO_2 and H_2S can be highly corrosive. Internal factors that contribute to corrosion may include [36]

- Oxygen content or reactivity of liquids and gases carried
- Not coated areas
- The temperature, flow rate and pressure of the gas

Uniform pipe corrosion causes loss of the material along the non-coated area. Resulting in a continuous thinning of its solid structure.

Electrolytic corrosion

Electrolyte is a conductive medium that allows electrons to be transferred from anode to cathode. Electrolyte is a common word for water-soluble, charged substances such as water, rain, dew, snow, high humidity, or sea spray. They are either positively charged ions, known as cations or negatively charged ions, known as anions.

Electrolytic corrosion is a process of accelerated corrosion. When two metals are in contact with an electrolyte, the metallic surface of the anode (the lesser noble metal of the two) is continuously corroded by the cathode (the more noble metal) The term electrolysis means: The process of decomposing a chemical compound by passage of an electric current. Meaning that even two similar metals can form the cathode and anode of a cell, resulting in an unintended electrolytic cell [5] shown in Figure 6.

Exposing a metallic surface to an aqueous electrolyte, will start an anodic reaction producing electrons in the metal (oxidation). Cathodic reaction consumes the electrons produced (reduction). These make up a corrosion cell. The anodic reaction engages the chemical change of metal to form either soluble ionic product or an insoluble compound of metal usually an oxide. For cathodic reaction, oxygen gas generated could be reduced or water is reduced to produce hydrogen gas. The co-occurrent reaction of the anodic and cathodic reactions produces the electrochemical cell.

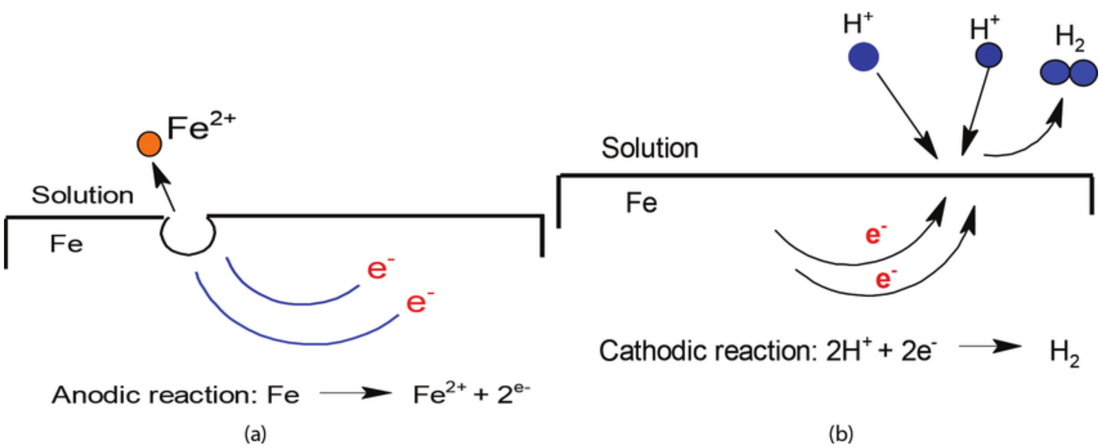

Figure 6: Anodic (a) and cathodic (b) reaction in metal/solution interface [6]

Corrosion of iron in contact with acidic water gives the following oxidation reaction

Equation 1 [7]

$$Fe \rightarrow Fe^{2+} + 2e^{-}$$

At the same time a reduction reaction will occur. Normally it will develop hydrogen gas or reduction of oxygen from air or water

Equation 2 [7]

$$2H^{+} + 2e^{-} \rightarrow H_2$$

Equation 3 [7]

$$\frac{1}{2}O_2 + 2H^{+} + 2e^{-} \rightarrow H_2O$$

Iron can also further produce the following reaction

Equation 4 [7]

$$Fe^{2+} + \frac{3}{2}H_2O \rightarrow \frac{1}{2}Fe_2O_3 + 3H^{+} + e^{-}$$

General corrosion often gives a nearly uniform solution over the entire surface that is in contact with water. Rust can be a mix between solid iron oxide (Fe_2O_3) and dissolved iron hydroxide ($Fe(OH)_3$).

Hydrogen sulphide corrosion

Hydrogen sulphide (H_2S) is an aggressive gas which can affect steel by making hydrogen sulphide corrosion. The process starts if H_2S is in contact with moisture, resulting in a chemical reaction that make sulfuric acid. This sulfuric acid has a corrosive effect on carbon steel, and corrosion rate with sulfuric acid will increase with temperature. Even weak sulfuric acid reacts with metals through a single displacement reaction. It attacks reactive metals such as iron, aluminium and nickel.

Equation 5 [8]

$$Fe + H_2SO_4 \rightarrow H_2 + FeSO_4$$

3.6 Black Powder

Black powder is a widespread and complex problem within the oil and gas industry. It is a general term used to describe corrosion related contaminates found in pipelines that transport gas, hydrocarbon condensates, and liquefied petroleum gas. The solids have been found to consist of a mixture of various materials. Among these are iron sulphide, iron oxide, dirt, sand, salts, chlorides, carbonates, glycols [9]. The most common of these are iron sulphide (FeS) and iron oxide (FeO), which are products of corrosion of the steel pipe, because of chemical or biological interactions in the presence of water [9]. It is important to remember that there is no straight forward solution to how black powder occurs. The name is given because the material is always black. Iron sulphide is black, and iron oxide is dark red/orange. But the presence of just a little of either of these will cause all the material in the mixture to turn black, see Figure 7.

Figure 7: Sample of black powder [2]

Most commonly, iron sulphides convert to iron oxides immediately upon removal from the pipeline when they are exposed to air[35].

Equation 6

$$4FeS_2 + 11O_2 = 2Fe_2O_3 + 8SO_2$$

This can cause difficulties since iron oxide can spontaneously combust when exposed to air. The main worries with black powder in pipelines are the potential for creating wear, and it may accumulate and clog instrumentation, valves, pipes and equipment, such as heat exchangers, leading to flow issues.

Characteristics of black powder solids are [2]:

- Very fine contaminates, forming agglomerates in micro size range. Typically, 1-10 micron
- Easy to transport, difficult to capture
- Is pyrophoric
- Need for appropriate handling and disposal procedure

Estimating amount of black powder

Information from pigging experts gave the knowledge about the amount of black powder in the uncoated joints to be a maximum of 20 g per joint over a ten-year period. There is a joint every 12m on the 800km long pipeline.[4]

Maximum amount of black powder estimate:

$$\frac{800\ 000\text{m}}{12\text{m}} \approx 67\ 000\ \text{ joints}$$

$$67\ 000\ \text{joints} * 0{,}02\text{kg} \approx\ 1300\ \text{kg}$$

This gives an amount of approximately 1300 kg black powder. Due to the consistency, some of this powder remain inside the pipeline after the pigging operation is done. After the last pigging, 10 years ago, there was at least 60kg black powder remaining, and this was transported out with the gas delivery and ended up in the downstream system.

Temperature, flow velocity, and surface condition of the metal can influence the presence of corrosive components. For example, condensation of water and hydrocarbons can be a result of temperature reductions, creating a more corrosive environment. Higher velocities can lead to increased turbulence and accelerated corrosion [32].

3.6.1 Appearance of oxygen

In theory there is not supposed to be free oxygen present in the gas pipeline. The producing platforms have instruments analysing the gas prior to it leaving the platform, to meet the pipeline specification. The maximum allowed under the specifications for Gasscos system is 2 ppm with oxygen. After gathering more information and studying the chemistry that takes place, it has emerged that oxygen does not have to be free oxygen (more about oxygen in chapter 3.5.2). However, it can come from the breakdown of other compounds containing oxygen atoms. This makes it a possibility that there in fact can be oxygen reactions in the natural gas. Even trace amounts of oxygen are sufficient to cause corrosion.

3.6.2 Appearance of water

Same as for the oxygen, in theory there is not supposed to be any water present in the gas pipeline. The natural gas goes through a gas drying process before leaving the platform. This is mostly done by saturating the gas with TEG from the glycol contactor. Wet gas enters the TEG contactor inlet at the bottom and passes through the glycol contactor. Glycol flows into the contactor tower from the top. These two phases meet, TEG will attract water molecules from the gas, and the gas will contain some TEG when leaving the contactor. Further on the TEG/gas mixture then goes to the scrubber. The scrubber's job is to transfer the heavier components in the gas phase, to become liquid. So that they will not condense at a later point. All the TEG is supposed to be taken out from the gas in the scrubbers. The drying is done to meet the export gas specifications before entering the pipeline.

[4] Estimate from pigging company T.D. Williams

The problem occurs when some of the TEG changes into gas phase, and then follows the gas stream in the process. Natural gas has a low water dewpoint, approximately –18 °C at 80 barg. Since TEG has a higher dewpoint than natural gas, the TEG (although only a small quantity) might condense as the temperature and pressure of the natural gas decreases.

The liquid glycol in the pipeline will equilibrate with the water in the gas. The resulting water content of the glycol will be determined by the water content of the dry gas, as the glycol will capture some water molecules from the gas. The corrosion rate is determined by, gas composition, temperature of the liquid, and the water content of the glycol/water solution[5].

Figure 8 shows the dewpoint for hydrocarbon gas, and the water dewpoint with TEG. This illustrates the two different fluids not having the same dewpoint. The natural gas dewpoint are inputs from Table 2 and the TEG dewpoint is found in the data sheet[2]. From the dewpoint diagram it is possible to see that TEG containing water molecules will condense at a higher temperature then hydrocarbons. This supports the thesis that water molecules may be present inside the pipeline.

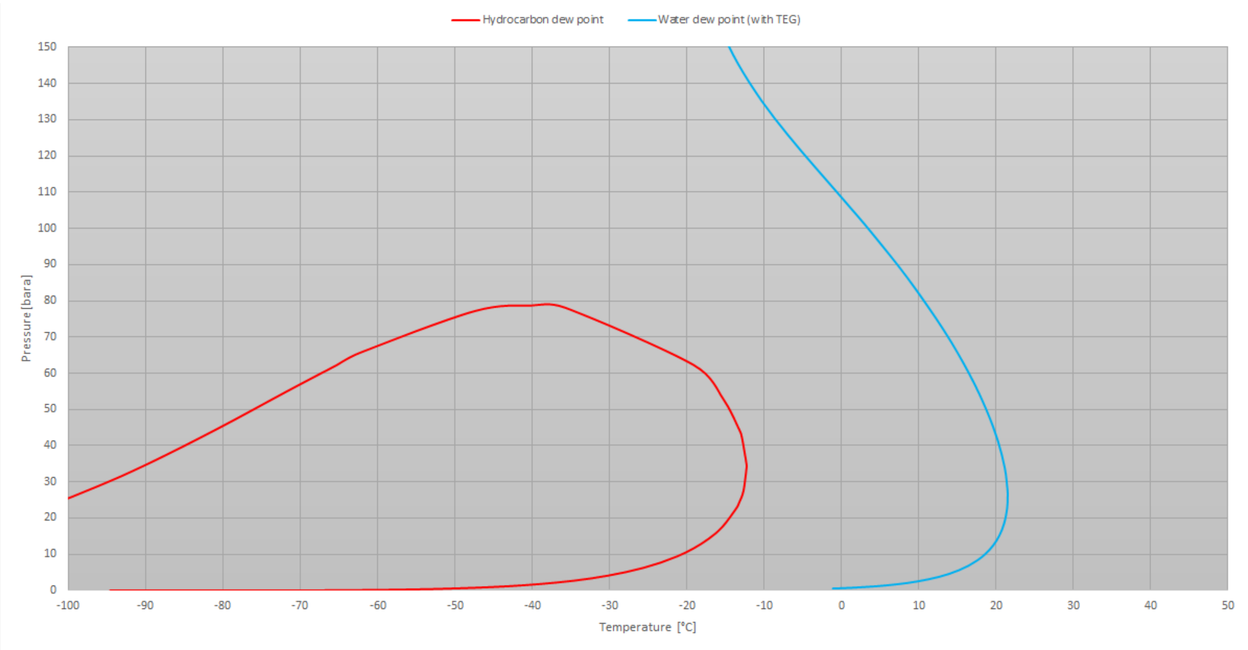

Figure 8: State diagram for TEG dewpoint [2]

The TEG water might therefor condense inside the pipeline as the temperature and pressure falls gradually. This can also create a weak electrolyte. The TEG-water mixture, although much less corrosive than pure water, is still corrosive. Expected corrosion rates are low (<0.1 mm/year)[13]. Attachment 2, concentrated lab rapport pipeline, shows that there is a small amount of TEG present inside the pipeline. It should be noted this sample is concentrated, as the sample was collected after a pigging operation performed in 2010.

[5] Information from Leif Idar Langelandsviks, Senior adviser, SO-OS, Gassco AS

3.6.3 Carbon dioxide

Carbone dioxide (CO_2) is a natural compound found in natural gas, with various amounts depending on the reservoir. Before the gas leaves the platform, it is analysed, and the specifications stipulate it cannot be above 2.5 mole% according to Table 2.

CO_2 corrosion is one of the most common corrosion mechanisms that occur on carbon steels in the oil and gas production and on processing systems [14]. The most important parameters for CO_2 corrosion are temperature, partial pressure of CO_2, pH, content of organic acids and flow conditions. The presence of H_2S in combination with CO_2 influences the corrosion of carbon steel (see chapter 3.5.2). The type of corrosion is dependent on the proportions of these constituents in the production fluids.

3.6.4 Hydrogen sulphide

Hydrogen sulphide (H_2S) [43] is a natural compound in natural gas from the reservoir. It is formed when there are chemical and bacterial reactions within hydrocarbon system. The main reactions that lead to production of H_2S in the gas reservoirs, are bacterial sulphate reduction and thermochemical sulphate reduction. Organic materials rots without any oxygen present, so the waste from bacteria living in the reservoir, will follow the well stream, and later on the gas stream. The maximum specification of H_2S is 5 mg/Nm^3 [2]. H_2S is a colourless, flammable, poisonous and corrosive gas.

H_2S is one of the reasons why black powder occurs. The problem with H_2S is the possibility of reacting with oxygen in the gas stream. This will create an environment which will impact the uncoated pipeline construction. After H_2S reacts with oxygen, free sulphur appears and can further on react with the iron, where the pipeline is not coated with protective coating.

For carbon steel, general mass-loss corrosion caused by H_2S-dominated corrosion conditions is rarely a problem, since the iron sulphide scale is generally protective[14]. However, if the scale is damaged, then localized pitting corrosion can occur. Deposition of elemental sulphur or solids due to stagnant flow conditions may promote such localized corrosion. No generally accepted corrosion models exist to predict this form of localized attack, and the evaluation should therefore be based on operational experience.

3.6.5 Free sulphur

Sulphur (S) is one of the elements found on the periodic table of elements. One of the traits to identify pure sulphur is that it forms a yellow crystalline solid at room temperature [45]. The element can be found naturally in a pure crystalline form on earth, but sulphur can also be extracted from molecules through chemical reactions. The most relevant reaction to form sulphur to this thesis is when O_2 reacts with the H_2S in a gas stream within pipelines. When this chemical reaction takes place the hydrogen atoms in H_2S reacts with the oxygen, creating both H_2O and S. This reaction may in the end cause sulphur deposits within pipelines [45].

The presence of sulphur within steel pipes may accelerate the corrosion rate where it can even react directly with Fe [47].

Equation 7

$$8Fe + S_8 \rightarrow 8FeS$$

Sulphur may also form sulphuric acid H_2SO_4 through hydrolysis if the right conditions are met [47]. Hydrolysis is a chemical reaction with water, leading to decomposition of both solid and water [46]. This sulphuric acid causes a sour environment which increase the corrosive rates.

Equation 8

$$S_8 + 8H_2O \rightarrow 6H_2S \ + 2H_2SO_4$$

Sulphuric presence may also influence the uniform corrosion rate of carbon steel and induce localized corrosion due to high sodium chloride concentration or high pressure [45]. From Equation 7 and Equation 8 it is clear that presence of sulphur in the gas pipelines may cause an increase corrosion. Ahead of the observations of elemental sulphur dust in other gas pipelines, there was not any focus on the consequences this could have. Based on this it is recommended doing more studies regarding free elemental sulphur.

3.6.6 Iron oxide

Taking things down to the atomic level to examine the difference between ferrous oxide and ferric oxide. This is done to explain both iron oxide and iron sulphide. To understand the difference, there needs to be an understanding of oxidation. Oxidation occurs when a chemical reaction causes electrons to move. When a substance loses electrons, we say that the substance has been oxidized.

Ferrous oxide is another name for the chemical compound iron (II) oxide or FeO. The name ferrous indicates that iron is in the +2-oxidation state [15]. And has lost two electrons to form Fe^{+2}. This will make it able to bond with other atoms that have an extra 2 electrons. Ferrous oxide is a black-coloured powder with a molar mass of 71.84 g/mol.

Ferrous oxide is produced through the combination of ferrous and oxide ions.

Equation 9 [15]

$$Fe^{2+} + O^{2-} \rightarrow FeO$$

Ferric oxide is another name for the chemical compound iron (III) oxide, or Fe_2O_3. Ferric oxide is a red-coloured powder with a molar mass of 159.69 g/mol. The ferric oxide is formed by combining two ferric ions with three oxide ions (magnetite). While iron in the +3-oxidation state is called the ferric ion, and iron (III) oxide is ferric oxide. The most common iron oxide is rust. If there is water vapor present, there is oxygen in the water. From this oxygen, Iron oxide can occur.

Reaction of ferric oxide

Equation 10 [15]

$$2Fe^{+3} + 3O^{-2} \rightarrow \ Fe_2O_3$$

3.6.7 Iron sulphide

Iron (II) sulphide is known under another name ferrous sulphide and comprises a formula which is noted as FeS. This mineral is created through a highly exothermic reaction where iron combust with sulphur forming Iron (II) Sulphide. The formation of iron sulphide happens according to the equation given below

H_2S from the gas, reacting with oxygen

Equation 11 [33]

$$2H^{+}{}_{2}S^{2-} + O_2 \rightarrow 2H^{+}{}_{2}O^{2-} + 2S$$

Iron from the pipe, reacting with sulphide

Equation 12 [34]

$$Fe^{2+} + S^{2-} \rightarrow FeS$$

Body of knowledge black powder

Research shows black powder to be a common contamination found in pipelines transporting gas [40]. However, the mechanism of black powder formation in these pipelines is a complex matter. The group has done extensive research on the subject but has not been able to find the information needed to get further knowledge.

3.7 Pigging

The gradual build-up of debris, grease, corrosion, and fractures within gas pipelines are serious problems that can cause flow assurance issues, plugging of the pipeline and, in extreme cases, result in accidents. A pipeline pig is a maintenance tool which can help mitigate these issues and provide optimal flow assurance. The name is an acronym for “pipeline inspection gauge”.

3.7.1 How does pigging work

The pig is introduced to the pipe through a system consisting of a launcher and a receiver. Collectively these are known as pig traps. The launcher releases the pig from one end of the flow line, and the receiver retrieves it at the other end. The pig is usually a cylindrical or spherical device as shown in Figure 9. It travels through the pipeline by using the force of the fluid flowing through the line without interrupting the flow too much. There are several functions the pig can perform as it travels along the pipeline. Such as clearing and cleaning the line, sweeping the line by scraping the sides and pushing the debris ahead to ensure optimal flow integrity, and inspecting internal sections of pipelines to plan for remedial operations [16] [17] [18].

Figure 9:Pig entering pipeline [17]

There are different criteria the engineers must consider when selecting the proper pig.

1. Define the task the pig is performing
2. Regard the size and operating conditions
3. Pipeline layout

There is not one definite schedule for pigging a line because every pipeline is different. The quantity of debris collected and the amount of wear and tear on the pipeline can increase the frequency of pigging. Figure 10 show debris after a pigging operation. Pipeline pigging is used during all phases of the life of a pipeline today.

Figure 10: Debris after pigging operation [18]

3.7.2 Types of Pipeline pigs

For the most effective result it is essential to select the appropriate pipeline pig for the job. Although first used simply to clear the line, the purpose of pipeline pigging has evolved with the development of technologies. The following are some common pipeline pig types used in the oil and gas industry today. Pigging content is obtained from [16] [17] [18].

Utility pig

Utility pigs are used for cleaning, dewatering and sealing. During construction debris can accumulate, and the pipeline is pigged before production commences. Debris and semi-solids that obstruct or limit the flow of hydrocarbons can also build up in the pipeline, and the utility pig is used to scrape it away.

Utility pigs can be divided into the following types:

- Mandrel Pigs – Consist of a steel mandrel body and has a series of replaceable sealing elements such as cups and discs. Mandrel pigs contain special brushes that remove debris from the internal sections of pipelines. This type of pig is cost-effective, and worn-out components can be replaced resulting in a brand-new pig. A bidirectional (Bi-Di) pig a is an example of mandrel pig pigs that has a bi-directional design which allows the pig to run in either direction in the pipeline.
- Solid Cast Pigs – Consist of a single piece of polyurethane polymer or steel.
- Foam Pigs – Consist of a combination of polymer foam embedded with solid abrasive materials.
- Spherical Pigs – Consist of hollow, spherical balls made from polyurethane or neoprene. These pigs are mostly filled with liquids such as glycol or water and inflatable to retain their shape within gas pipelines when exposed to the high pressures.

Inspection pig

Inspection pigs are also known as smart pigs and as in-line inspection pigs. These contain electronic components and gather information such as diameter, curvature, bends, temperature and pressure within the pipeline, as well as corrosion or metal loss. There are two main different methods to gather the information about the interior conditions.

- Magnetic flux leakage: Detecting leakage, corrosion, or flaws in the pipeline by sending magnetic flux into the walls of the pipe.
- Ultrasonic: Using ultrasonic sound, measuring the time an echo takes to return to the sensor, to directly measures the thickness of the pipe wall. Figure 11 show an inspection pig.

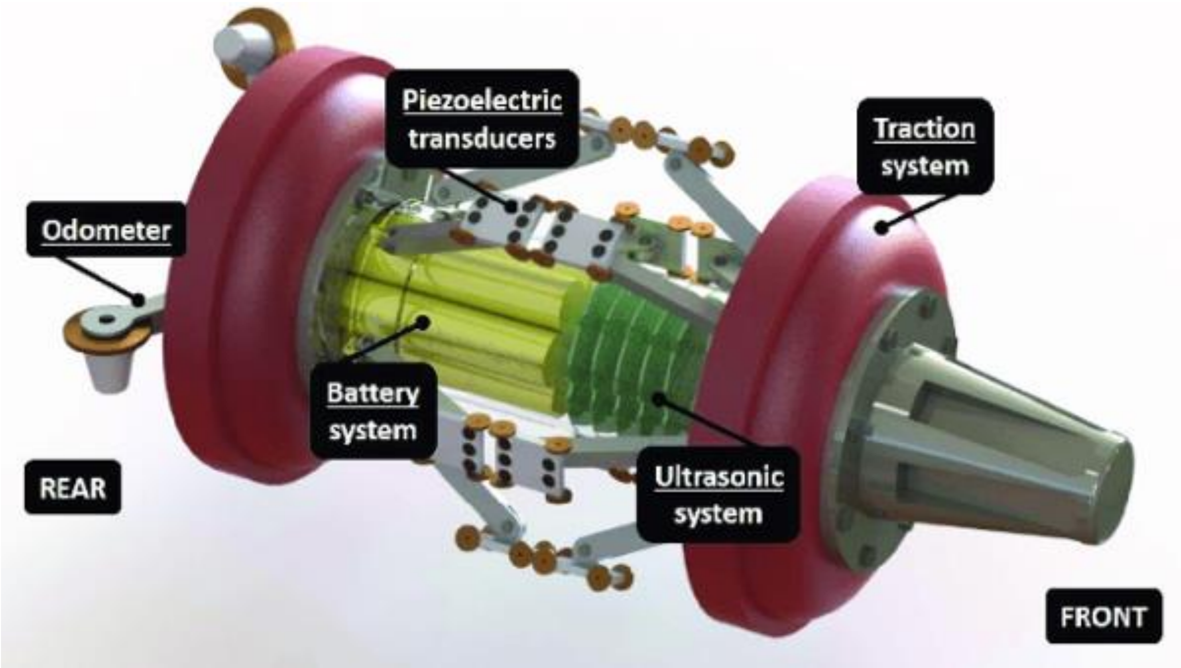

Figure 11: Inspection pig [19]

Specialty pig

Specialty pigs are also called plugs and can isolate an entire section of the pipeline at pressure while remedial work is being done. These pigs are used for pipeline maintenance work and cleaning. The plug works by gripping into the line pipe and then having a separate sealing system. Figure 12 show specialty pigs creating a sealing system.

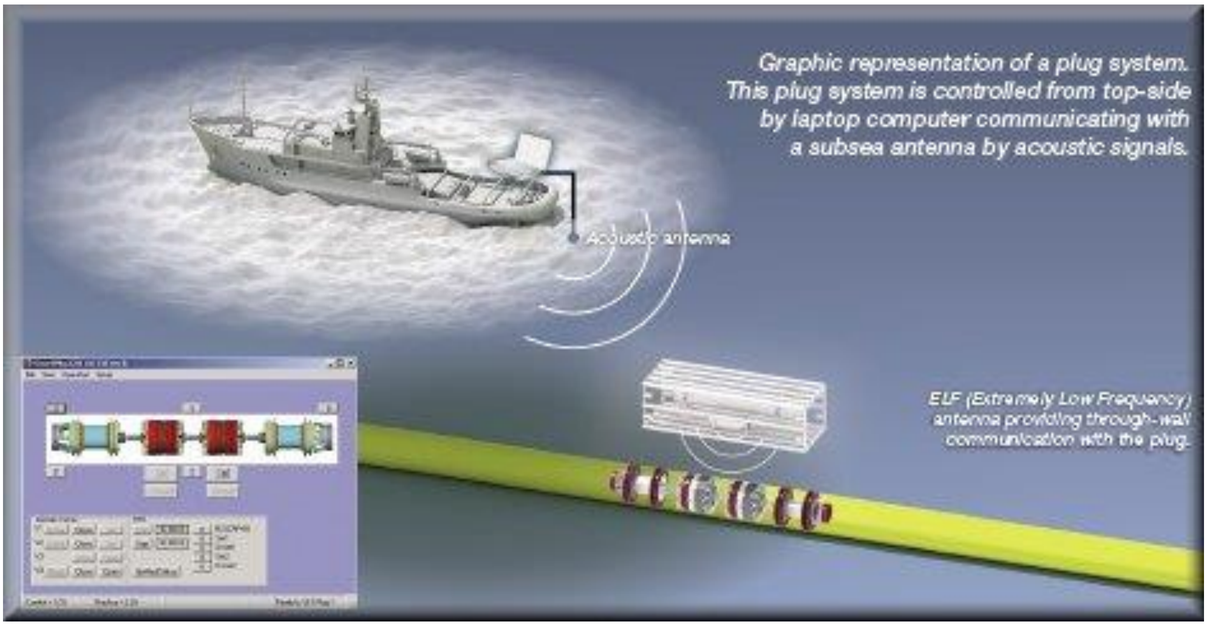

Figure 12:Specialty pig [18]

Gel pigs

Gel pigs are a combination of gelled liquids such as rigid polymers and high-viscosity gels, making them non-solid, and can be used by themselves or in conjunction with a conventional pig. There are several uses for gel pigs. Some examples are, hydrotesting, debris removal, product separation, dewatering and condensate removal, as well as removing a pig stuck inside the pipeline.

They are the ideal option for so-called “un-piggable” lines – pipelines. These are pipelines consisting of sharp bends, internal valves, and/or special structures that could result in a stuck pig. Gel pigs do not require a launcher and receiver system, and are often used alongside other types of pigs to prevent deterioration of the primary pig components and improve efficiency.

3.8 Elaboration of the issue

The sponsor Gassco are having trouble with black powder build up in this thesis terminal, this appears after pigging operations. The problem is not a major concern at this point, but there is a possibility of an unplanned shutdown because of debris clogging the heat exchangers on the receiving terminal.

The sponsor already had external companies to study the issue, however their solutions were costly and intrusive. Gassco asked the group to be innovative and think outside of the box, to see if there were other solutions.

- How to ensure contaminant free gas delivery
- Is it possible to eliminate the problem
- If not, what should be done to mitigate the problem.

The authors collected and analysed information from the sponsor and companies specialising on pigging and black powder. This was done to get familiarised with the issue, before information from books and webpages on the subject was gathered and read. After these studies were done it was time to start brainstorming ideas and finding plausible solutions.

4. Results

After an extensive research and development phase, there were several solutions deemed viable and worthy of further investigation to mitigate the black powder issue. The following chapter shows the alternatives presented for the sponsor.

4.1 Proposals assessed focused on eliminating the issue

4.1.1 Injecting chemicals

One suggestion that was raised as a possible solution was to inject chemicals into the gas pipeline. The chemicals that would be recommended to inject into the pipeline are a H_2S scavenger, mono ethylene glycol or diethanolamine for their corrosion inhibitor properties [29] [30] [32]. Injecting corrosion inhibitor is a process to maintain and extend the lifetime of a gas pipeline by reducing and/or preventing the corrosion from occurring. When injecting chemicals, it is critical that the dosing of the chemicals is accurately regulated as both too high and too low doses result in a significant effect on the corrosion inhibiting properties of the chemical. The corrosion inhibitor adsorbs onto the steel surface and slows down one or more electrochemical reactions [32].

Diethanolamine

The presence of CO_2 in natural gas can be stabilised by injecting small doses of Diethanolamine [29]. This will act as a pH stabiliser in order to reduce corrosion, as a low pH value increases the rate of corrosion. (See Carbon dioxide in chapter 3.6)

H_2S scavenger

Hydrogen sulphide scavenger is one method to minimise the operational risk and corrosion in pipelines. These specialised chemicals react selectively with and remove H2S to help meet the product and process specifications. This chemical is being injected to remove H2S from natural gas[6].

Ethylene glycol

Ethylene glycol is mainly used for its hydrate control [39]. It also has an inhibitive effect on corrosion which comes from dilution of the water phase leading to removal of water molecules from the fluid [30].

4.1.2 Coat the joints

When the pipelines are laid on the bottom of the ocean, they are welded together every 12 meters. The 12m pipe sections themselves are coated with chemicals to prevent and protect it from corrosion (most commonly used is Epoxy or other coating recommended from vendor.[7])However, the joints where the sections are welded together cannot be coated due to the chemical reaction that might occur due to the heat from the welding. It could also cause a bad weld that would not be strong enough. This is the reason the joints are the main problem where black powder occurs. With this in mind, the authors came up with an idea for a solution to coat the joints after the pipes already have been laid, using a specialty pig.

[6] Information from Elin Klemp Smith, Process engineer. Neptune Energy

[7] Information from Jan Gunnar Tangen, Frosio inspector level 3, Aibel

4.2 Proposals assessed focused on mitigating the issue

4.2.1 Pigging program

For the thesis pipeline, investigating increased pigging frequency, or changing types of pig being used would be recommended. If pigging frequency increases, there is a possibility that black powder within the pipeline will not get a chance to build up. By changing the type of pig being used there is a chance of better cleaning performance when executing the pigging programme.

The build-up issue has the potential to affect the production, and in a worst-case scenario, cause a shutdown of the processing system. It might be possible to reduce the build-up of black powder particles within the pipelines, and maybe a more frequent pigging be the solution. If this would not lead to even more contamination. However, the group believes that changing the type of pigs being used may have a positive effect on cleaning efficiency. The following pigs were proposed:

Pig with electromagnet

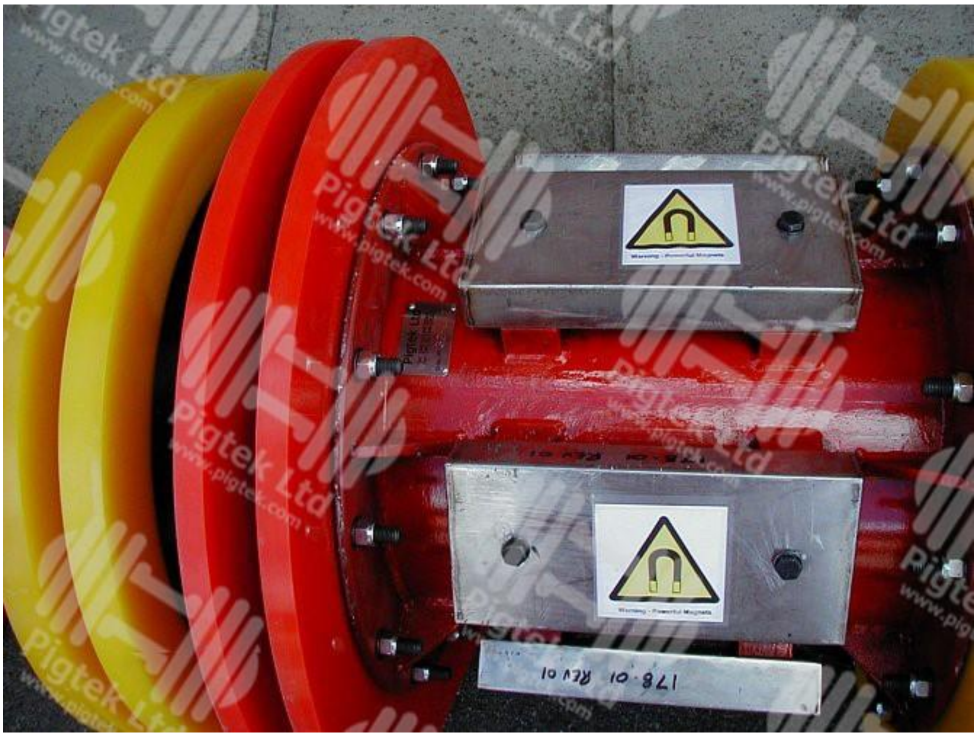

Figure 13: Magnetic pig [20]

Magnetic pigs are sent in the pipeline to remove magnetic ferrous debris from the pipeline. The magnets are usually attached to the body of the pig, as shown in Figure 13. As this makes them more effective in collecting debris. The electromagnets will attract the magnetic debris and keep it there until the pig reaches the pig trap. Electromagnetic pigs are specialised pigs fitted with powerful magnetic package in multi-pole design, which provides a huge magnetic field across a vast surface area to ensure pick-up and hold capability. A magnetised pig usually has a steel body, which has magnets attached to it [20].

The group has a hypothesis that by sending a pig that is electromagnetic, this can attract the black powder. The black powder will then stick to the pig, and in theory follow the pig until it is recovered in the pig trap. To achieve this, one or more cleaning pigs must be sent in advanced, at a short time interval. Once the powder has loosened from the inner wall, the magnetic pig will be sent through the pipeline to collect the loose powder

Pig with filter element

This type of pig is an innovative idea that does not currently exist. Some of the problems the sponsor flagged, is that after the pigging, the receiving terminal receives black powder which can congest/clog the process equipment. Therefore, the authors came up with this innovative idea; See if it is possible to design a pig with filter element similar to a "vacuum cleaner bag", which would collect particles as the pig travels through the pipeline. Figure 14 shows how this pig would be designed. The design must contain a very fine filter to be able to collect the black powder. The filter element should stick around the rod in the middle of the pig. In the front of the pig, there must be an opening for the gas and particles to enter.

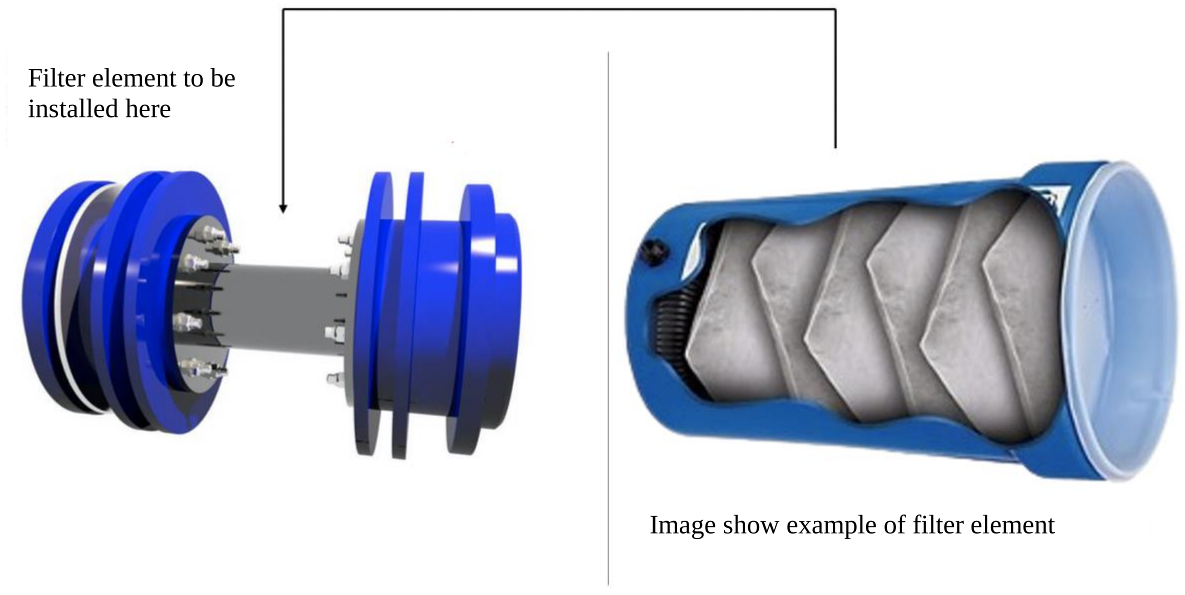

Figure 14 Pig with filter element, designed by one of the authors, Gudrun Stol

Pig with gas blasting function

Sandblasting is used to remove unwanted corrosion from materials. Sand is blown out of a nozzle at high pressure such as 7 bar[8], and when the sand hit the material, the corrosion is removed. Using the same principle, the gas flow could be used to gas blast the pipe joints with the pig. In the front of the pig there are nozzles, these can be opened at a specific pressure so that the gas passes through. A brake system holds the pig so the pressure can build up inside the pig, and then open the nozzles. See Figure 15. When the nozzles open, the pressure needs to be at a specific level to blast the black powder loose. After the powder is loose, it will be transported with the gas flow in front of the pig, leaving less residue of black powder in the pipeline after this pigging operation. Normal

[8] Information from Jan Gunnar Tangen Frosio Inspector Level 3, Aibel As

operational pressure is 75-145 barg so the pig needs to plug the pipeline as mentioned above, while the pressure builds up to get the wanted pressure for this operation.

The principle of this pig is to launch it and make it gas blast the pipeline in front of the pig, sending the black powder ahead instead of leaving it swirling behind the pig. If this solution works like the authors visions, there will be much less black powder left in the pipeline, and it is transported with the pig to the pig trap onshore.

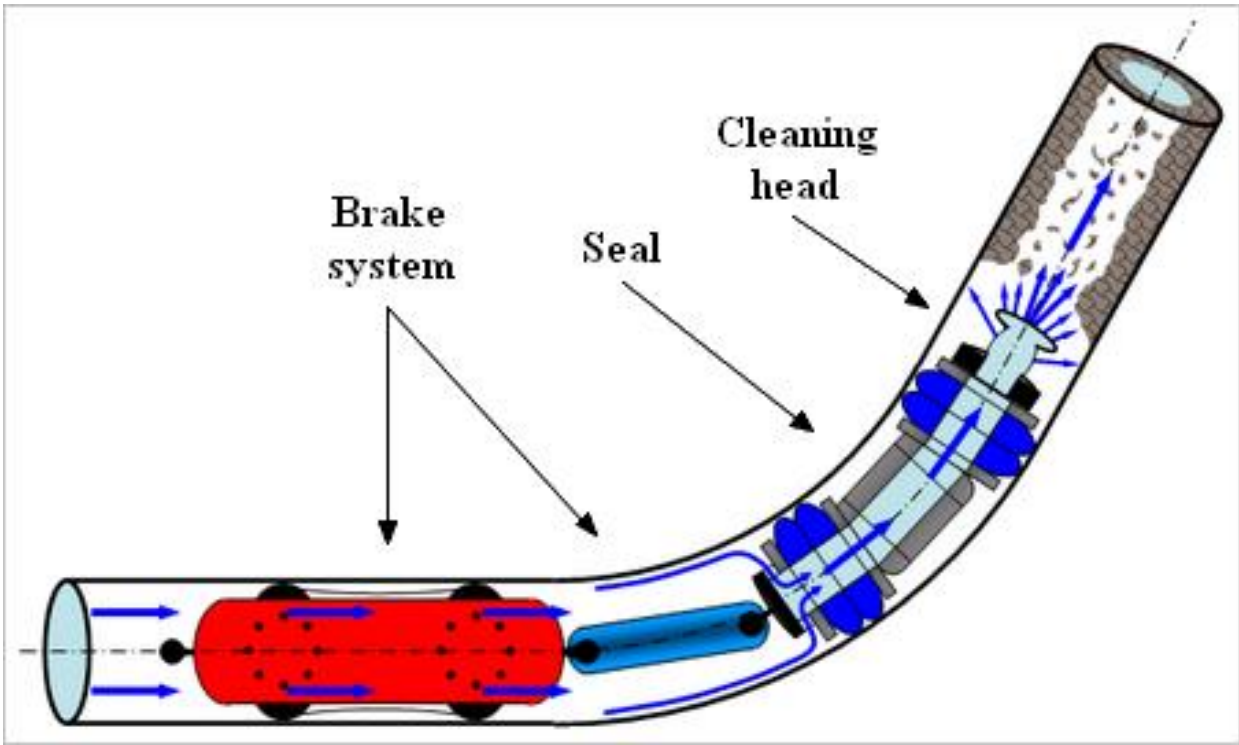

Figure 15:Gas blasting pig [21]

4.2.2 Cyclone Filter

Cyclone filter is a hybrid solution that combines the functions of a cyclone and a filter. The cyclone provides mechanical uninterrupted operation and makes sure of removing the coarsest particles down to 5-10 microns. The filter ensures efficient gas purification and removes the finer particles down to the requested specifications. As seen in Figure 16, contaminated gas flows into the filtration chamber and centrifugal force due to the cyclone cleans the gas. From this stage, only the gas stream rise to the top of the cyclone and goes through a filter to get rid of all the contamination. Due to the cyclone, the filter does not need to be replaced as often since the coarsest particles are removed by the cyclone. This makes the cyclone filter a less maintenance intensive than a single regular filters stage, and a lot more effective than just cyclones [22]. Cyclone filters are intended to extract dry dust from gasses in all industry sectors and are dimensioned according to the design basis.

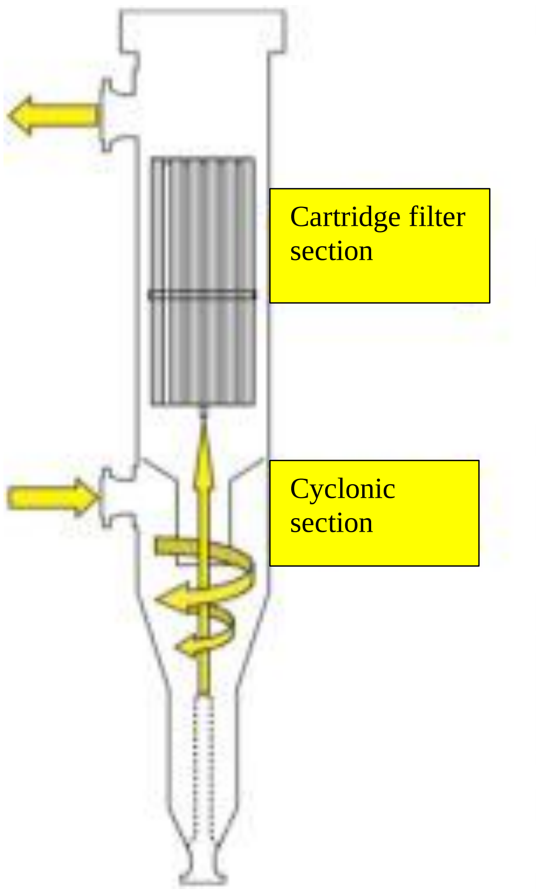

Figure 16: Cyclone filter [2]

This solution has been considered by Gassco as well. The already existing cyclones performance is not satisfactory and does not clean the gas well enough. Since there is an existing cyclone at the terminal, replacing it should not cause too much piping modifications, and therefore the costs are expected too also be manageable. Considering both cyclones and filters are familiar to the operators at the site, and the addition of a filter should not lead to too much additional maintenance activities, this appear to be an attractive and viable solution.

4.2.3 Electrostatic Precipitators, ESP

The following information is collected from [23]. Electrostatic precipitators, often referred to as ESP, use the advantages of charged particles and electrical energy to separate unwanted dust particles from the flowing gas stream. The particles get either negatively or positively charged and are then attracted to collector plates carrying the opposite charge. The collected particles may be removed as dry material; dry ESPs, or they can be washed from the plate with water; wet ESPs. An ESP is primarily made up of the following four components: discharge electrodes, gas distribution plates, rappers and collection surfaces (either plates or pipes). The gas distribution plates consist of several perforated plates which help maintain proper flow distribution of the entering gas stream. See Figure 17 on how the gas flows through an ESP.

The discharge electrodes, energised by transformer rectifier set and power supply, are divided into fields. Most ESPs have three or four fields in series, however very large units may have as many as 14 fields in series. The energised electrodes create ions that collide with particles and apply the electrical charge to the particles contained in the incoming gas stream. The collection plates or pipes provide the collection surfaces for the charged particulate matter. The rapping system is responsible for removing the collected particulate matter from the collection surfaces

This is a very effective way to clean the gas, in fact electrostatic precipitators are capable of collection efficiencies greater than 99 percent [23]. It also has low maintenance requirements. The main downside with this solution is that it will be hard to make it fit since the design is physically bulky and would probably not fit onto the existing footprint available at the terminal in a viable location, leading to major re-design of existing pipework. It would also require some changes in the square design, as for a gas stream with the pressures relevant for this thesis, a square design will cause accumulation of forces in the corners, leading to massive loads on the materials and welds in the corners.

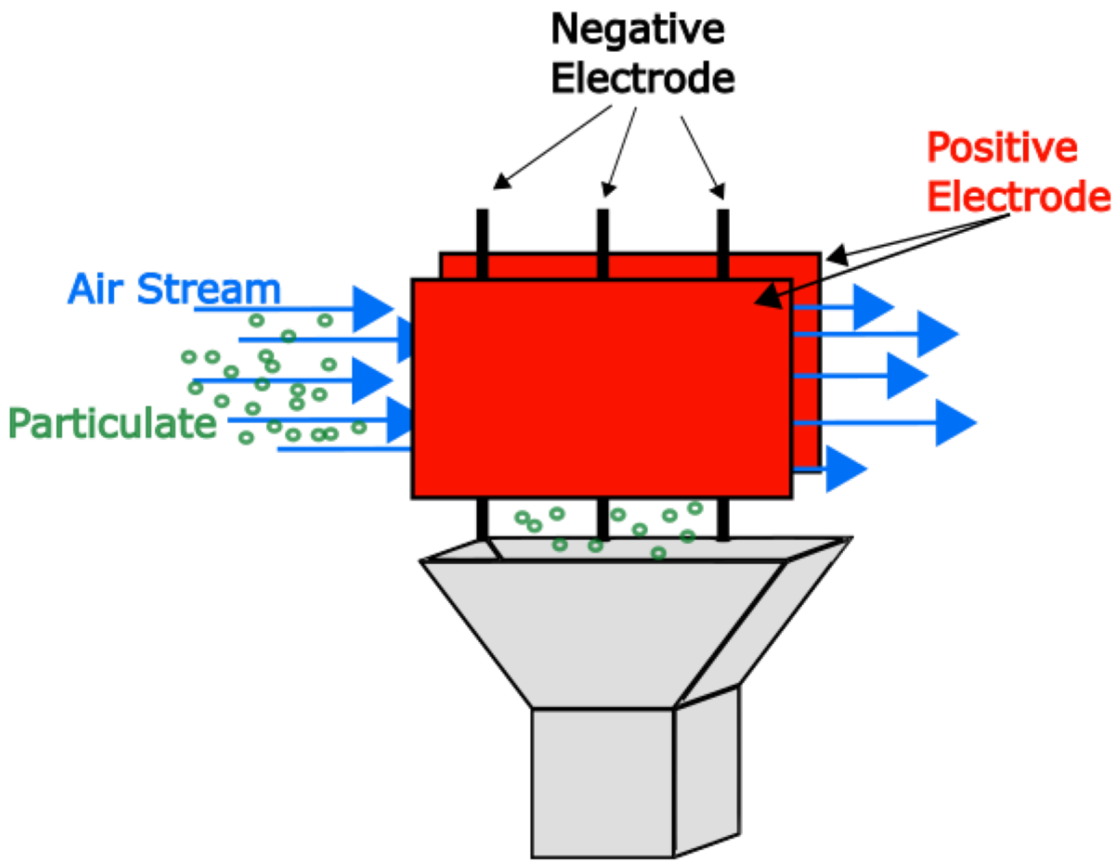

Figure 17: Electrostatic Precipitators [23]

4.2.4 Replace the existing cyclone separator

On the thesis terminal there is a gas cyclone separator on each of the three production trains. The cyclones have never worked as planned [2]. Cyclones without any further solid removal, are not suitable to achieve the removal efficiency stated in the project basis of design. Existing cyclones design solution should be able to achieve removal of solid particles down to 5-8 micron.[7] Therefor the suggestion is to change the existing cyclone separators, with properly designed ones that can separate particles more efficiently than those currently installed. Black powder particle size range is typically 1-10 micron.

For this Base Case (replacement of 3 x 50% vessels), keeping modifications, cutting & welding to a minimum was a significant driver in the design. Similar work will be required over the 3 trains, some of which shall be completed during separate shutdowns & train Isolations.

4.2.5 Installing filter

Today's receiving cyclone separator doesn't fulfil the established requirements for particle removal. Hence, the smallest of the particles won't be caught and removed from the stream. This is the reason why installing temporary or permanent filter element could be a good idea.

Temporary filtration requirements

By having a temporary filtration package, the sponsor can decide when they want to use the filter package. The secondary filtration system can be connected to pig trap discharge/kicker line. Points to consider:

- The flow capacity is dependent on filter element mesh size, viscosity, and quantity of debris
- The filter elements are designed to stop sand/debris transport, without obstructing liquid and or gas flow through the unit. Optimally, two is in use to facilitate cleaning of the third
- Rent or purchase equipment
- Extra manning need
- Spare parts philosophy

Permanent filtration

Another option is to install a fine mesh particle filter downstream the existing cyclone separator to absorb the remaining black powder. This proposed solution is in use at other terminals [2].

5. Discussion

After reviewing ideas and collecting data, an assessment looking into the strengths and weaknesses of every suggestion was made. In order to get the right assessment of the solutions, professionals within the relevant fields were also consulted. This was done so the conclusion would be as solid as possible. Technology is changing fast, so research will not be accurate without interviews with personnel working in the field.

5.1 Rejected proposals

The following solutions have been rejected due to reasons explained below.

5.1.1 Inject chemicals

The group has been researching the possibilities of injecting chemicals into the pipeline. This is in order to moderate the occurrence of oxygen, carbon dioxide and hydrogen sulphide, to eliminate the amount of corrosion inside the pipeline joints. The requirements set for injecting chemicals into the pipe is that it must be done in an early phase of the well stream. This is due to the naturally existing water/condensation in the gas which must be removed before the gas gets exported from the platform to the pipeline. This type of processed gas is referred to as dry gas once the water and heavier components have been removed. The reason why the water/condensation must be removed, is that the water molecules have a risk of bonding with other existing gas molecules. These can create a hydrate plug if conditions drop below certain parameters of temperature and pressure. Another reason to remove the water is to eliminate the corrosion. It is also crucial that the gas meets the set parameters by the receiving terminal onshore. The set gas parameters are shown in Table 2: Dry gas specifications.

Liquid in gas phase

By injecting liquids into the gas phase, precautions must be taken. Liquids are not to be present in the sales gas system. The sponsor said that if the chemicals could go from liquid to gas phase and dissolve, this might be a solution[9]. To see if this could be an option the vapor pressure of the gas and chemicals was studied. The vapor pressure is the partial pressure for a substance where it dissolves into gas from liquid to meet the necessary equilibrium at the pressure/temperature conditions.

Due to the vapor pressure versus the pipeline temperature and pressure, the chemicals will not change to gas phase. Also, the average natural gas through the pipeline contains maximum 2.5 mole% CO_2 and 5 mg/Nm^3 H_2S. This thesis does not support the idea that injecting chemicals will decrease the fraction of CO_2 and H_2S significantly, since the fraction is relatively low, and the chemicals might not reduce this further significantly. Therefore, this proposal was rejected.

[9] Information from Vidar R. Nilsen

5.1.2 Coat the joints

The problem with black powder occurs in the non-coated area inside the pipeline. The group thought of eliminating the problem area by coating it. When investigating this solution, a calculation was made to calculate how much of the internal area in the pipeline which is not coated. This was done to find out how effective coating the joints would be.

The numbers are rough estimates

About 95% of the inside of the pipeline is coated [2].

Parameters: D = 40” = 1016mm
L = 800km = 800 000m

Circumference: $\pi * D$
$\pi * 1{,}016\text{m} \approx 3{,}2\text{ m}$

Area: $3{,}2\text{m} * 800000\text{m} = 2\,560\,000\text{ m}^2$

This gives a total 2 560 000 m^2 of pipeline.

The uncoated area is 5%: $2\,560\,000\text{ m}^2 * 0{,}05 = 128\,000\text{ m}^2$

Industrial coating can be up to 4-6 kg per m^2 [38]. To show the amount of mass this could equilibrate:

Total mass of coating: $128\,000\text{ m}^2 * 4\text{ kg} \approx 500\,000\text{ kg}$

The positive side to this solution is that it would not require any design changes on the terminal. Nevertheless, major negative elements to this solution were found:

- It will be difficult to stop the pig every 12 m to spray paint the joints, since this would require an advanced navigation system
- Transporting hundreds of tons coating requires many pigging operations, which is something the sponsor would like to minimise
- The seabed ambient temperature makes it difficult for the coating to dry and cure may require a downtime period

To sum up, this idea was quickly dismissed because of the difficulties to implement, in addition to the major downtime period this may cause due to curing.

5.1.3 Different types of pigs

From the initial thesis start-up, different pig alternatives stood out as the most viable way to solve the problem. However, extensive research into the essence of the black powder, showed these solutions to be more complicated than first assumed.

Pig with electromagnet

The black powder that is causing an issue within the pipeline consists of different types of iron salts, where the majority turned out to be iron sulphide and not iron oxide[2]. This type of iron bounded salt is in fact not magnetic. Therefore, this would make the magnetic pig inefficient for cleaning/removal purposes. It is also important that the magnets should not be placed too close to the pipe wall, because there is a chance that the centre of the pig, between the steel mounting flanges, could become compact with ferrous debris. This could cause the pig to become lodged in the pipeline. Due to this discovery, the electromagnetic pig solution was discarded.

Pig with filter element

The pig with filter element was an innovative idea from the group. This is a completely new design, and its functionality has not been proven. The idea was that the gas flow would go through the filter element, and the filter element would catch the particles. A design problem is that the gas flow is pushing the pig to move forward. Therefor the gas will not be in contact with the filter element. It was proposed to install holes in the pig, so the gas could flow through, and then the filter element would catch the particles. This may be possible, but it might also decrease the gas force on the pig. Worst case scenario, the pig would get stuck inside the pipeline. After discussing this idea with the sponsor, the group decided that this pig was not a viable idea.

5.1.4 ESP Electrostatic precipitators

Electrostatic precipitators are mostly used for air purification, and the parameters given in the results are therefore not practical for usage in the gas industry. The electrostatic precipitators are used in low pressure systems [31]. The subject of this thesis is a high-pressure system. Therefor this option was quickly rejected.

5.1.5 Replace cyclone

Because a cyclone does not separate the smallest particles known to be in the black powder (typically less than 5-10 micrometres), it will not be able to separate all the black powder from the gas. Therefor replacing the existing cyclone will not be an adequate solution. There would still have to be installed filter element to separate the particles smaller than > 5 micrometres.

5.1.6 Installing filter

After receiving documentation in form of Piping & Instrumentation Diagrams (P&ID) and Process Flow Diagrams (PFD) from Gassco operated terminals, it has been observed that the other terminals have one or several methods for cleaning the gas. The most common is a cyclone separator and then a filter, as Figure 18 show. It can also be deduced from the other terminals that it is common to also have both rough and fine filters in order to optimise the separation process.

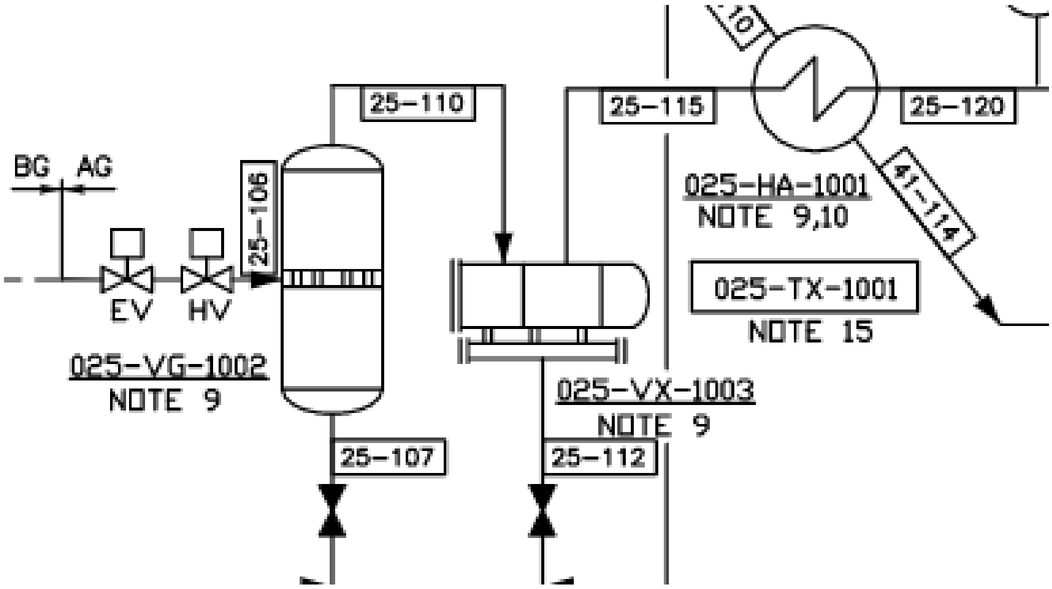

Figure 18: P&ID from Gassco operated terminal where they have permanent filter [2]

Further examination of the available plot uncovered other challenges. When installing a permanent filter, the authors believe two filter stages would be necessary, coarse and fine filter, because of the size of the black powder contaminant. Due to space limitations the two filtering stages would need to be integrated in to one vertical vessel. Based on feedback from sponsor, such vessel was not commercially available [2]. To install two filter stages would require major piping redesign, and this is something the sponsor would like to avoid. This idea was rejected due to these reasons.

Temporary filtration

Black powder seems to be an intermittent problem, so the group thinks this solution might be cumbersome. It is a major job installing and removing the temporary filtration skid, and it would be to challenging for normal operation, so the idea was rejected.

5.2 Feasible proposals

The following solutions are the ones the group find most feasible to implement.

5.2.1 Pigging pipeline

During the research process for this thesis, a suggestion was made to dig deeper into how the client maintained their pipelines with pigging operations. The last time a pigging operation was performed on the thesis pipeline was ten years ago. Considering black powder is not a problem in day-to-day operation, and only occur for a period after pigging, as the pigging operation disturbs the black powder on the piping wall. Increasing the pigging frequency was first looked into as a solution. However, there are uncertainties around the growth rate of the black powder on the uncoated parts of the pipeline. This makes it challenging to assess whether increased pigging frequency will increase or decrease the total amount of black powder passed on to the terminal.

Due to today's fast advancing technology, there has been a huge development within pipeline maintenance. Getting information regarding last maintenance program might give an insight on ways to possibly improve the efficiency of this operation. One possible solution was to change to a different type of pig to launch through the pipeline. Vendors wore contacted to explain the issue and discuss solutions. This resulted in one final suggestion that most likely will give the desired result.

Methods that can be used for limiting exposure time of powder in the system, is to run two cleaning tools together to bring the debris out between the two tools. If this is to be done, mobilisation of waste collection equipment and disposal bins for flammable / non-flammable waste must be available at site.

Enhancing cleaning efficiency/aggression:

Discs	For pushing/scraping. A disc only configuration will not provide enough wear compensation for a line of this length and debris types.
Cups	For wear compensation. Once a pig traversed the line and confirms pig ability, moving onto a uni-directional configured pig presents little risk
Bypass	Creating turbulence ahead of the pig. Helps keep debris suspended in the product ahead of the pig and prevent debris pile up in front of the pig. Can be used for pig velocity reduction, slow pigs to optimum speed for efficient cleaning
Brushes	At the right time and correct type. Full circular brushes are better than segmented brush at removing fine debris particles, whereas segmented brushes allow particles to pass below the brush head.
Magnets	For ferrous debris collection
Wheels	Providing centralisation and additional support, rotation may be induced to help ensure even wear on polyurethane component.

Dual-module pig configuration provides additional aggressive cleaning while reducing the overall numbers of runs required to ensure cleanliness.

The authors recommend the introduction of an entirely new pigging program like the one from iNPIPE. Implementing new technology pigs could, according to iNPIPE, potentially have the following (and possibly more) benefits:

- Reduce the pipeline operating costs
- Stabile flow, pressure, and velocity
- Remove debris

Pigging is a much more complex operation than first assumed. Therefor different companies and suppliers selling and producing pigs, was contacted. This was to collect the information, knowledge and experience with black powder and pigging pipeline. After emailing and having teams meetings. Of the solutions proposed, the group believes the following from iNPIPE is the most viable one.

Pigging program from iNPIPE PRODUCTS

iNPIPE PRODUCTS is an internationally recognised leader in the design and manufacture of pipeline pigging products. Figure 20 show iNPIPE logo.

Figure 19: iNPIPE logo [26]

Information given from the authors to the vendor:

- Pipe length: 800km
- Diameter: 40 “
- Working pressure: 75-100 barg
- Design pressure: $\approx$ 150 barg[10]
- Normal temperature: 2–14-degree Celsius
- Estimated amount black powder: 50-200 kg

The request from the authors to iNPIPE PRODUCTS

An inquiry was sent to iNPIPE, stating the authors idea that iNPIPEs magnetic pig could be the right solution. Further on they asked for documented information, and to arrange a meeting.

The meeting was set up and completed mid-March. The group found out that the black powder was not completely magnetic, so the idea of using a magnetic pig was no longer an option. The vendor recommended running a progressive pigging program where you run various aggressive brushes combined with mandrel Bi-Di pigs (see chapter 3.7.2 for more information about mandrel Bi-Di pigs). The brush pigs will disturb the black powder from the pipe wall and the Bi-Di pigs will then bring out the disturbed powder [37].

Solution from iNPIPE PRODUCTS

iNPIPE PRODUCTS recommend a project specific design incorporated, and they recommend sending one or several brush pigs with the features shown in Table 4, followed by a Bi-Di pig.

[10] Exact design pressure is confidential

Table 4: Brush pig features [37]

Feature	Purpose
AAA polyurethane formula	To have a light-weight-high-tensile aluminium body design
Multiple seal & support disc packages	To seal and support if necessary
Circumferentially mounted double fix point	To stabilise bearing
Torsion sprung suspension wheels	Centralise and support
Brush units	To loosen the black powder from the inner wall.
Bypass	Will be pluggable to enable velocity control in high-speed gas stream
360 Annular Jetting head	For 360-degree cleaning
Scrapper body design	To incorporate bypass to provide drive pressure to both the rear and front disc package of the tool

iNPIPE Case study from similar operations
INPIPE was approached to provide a design and manufacture solution to remove black powder from another company. On this job they used lightweight materials, bypass facility and jetting head design based on the type of debris present. Figure 20 show different pigs from iNPIPE.

Figure 20: Pigs from iNPIPE [37]

5.2.2 Pig with gas blasting function

When working through the proposed pig solutions, the group found the gas blasting pig as the only feasible option. This could be a way to solve the problem as it does not require any modification to the terminal. The concept of this pig already exists and could possibly be implemented as a part of the pigging program suggested above. Instead of brushing, gas blasting could be used to disturb the black powder from the walls. A positive effect with gas blasting could be that the Bi-Di pig might not be needed if the pig can remove the black powder without leaving residue. This by either blasting the powder down the pipeline in front of the pig or making this a 2 in 1 pig that can blast and scrape.

Although the solution is deemed feasible by the group, there are still uncertainties that would need further research. It is not known how much pressure the gas, leaving the nozzles, needs to be able to disturb the black powder, and remove it from the pipe wall. As mentioned, the normal pressure for sand blasting corrosion is 7 bar. To establish the necessary pressure for this operation, further calculations would have to be done.

5.2.3 Cyclone filter

After gathering information regarding the existing cyclone on the receiving terminal, the group found out that the cyclone separators are not working particularly well. After discovering this, the group wanted to suggest changing the existing cyclone separator with a cyclone filter. The cyclone filter has both a cyclone for removing the big particles and filter element for taking away the smaller particles. When choosing this solution, major redesign of the piping does not appear to be necessary. Some modifications are necessary, as the design of the existing cyclone and cyclone filter are expected to be different. It can also be challenging to finding plot-space for the installation, as space is limited. The group still believe that this is a better solution than changing the existing cyclone and installing stand-alone filters downstream these.

The cyclone filter should be possible to use during normal operation as well as after pigging operations. When more contaminants are expected. The existing configuration on the terminal is a 3 x 50% configuration, meaning during normal operation two trains will be in operation, and one train in standby. With this design, it will be possible to modify the standby train with minimal effect on terminal availability. Figure 21 show an example of a cyclone filter layout.

Figure 21: Cyclone filter separator layout [22]

Pressure
The pressure drop over the terminal is a crucial parameter for its capacity. Any equipment shall strive to keep any pressure drop to the absolute minimum.

Capacity
The cyclones filters must meet the existing capacity and should ideally have +10% from the existing terminal to have some margin and potential for future increases. This must be considered based on cost/benefit during Engineering. When a modification is proposed on a receiving terminal, the existing capacity must be maintained.

Removal efficiency
The system must be able to remove:

- 99.0% of particles ≥ 1 micron
- 99.5% of particles ≥ 3 micron
- 99.9% of particles ≥ 5 micron.

The system must be able to operate continuously even during the peak of contaminants expected during pigging operations.

Design criteria filter
The pipe coding on the system is:

- 24" – Carbon steel ASTM A 333 GR 6. According to ANSI B31.3
- Lines should be sized according to Norsok P-002 where relevant.
- Design temperature: -46/50 °C
- Design pressure ≈ 150 barg[11]

[11] Exact design pressure is confidential

6. Conclusion

From a process engineer's perspective, the most viable solutions to the case the sponsor presented would be to install the cyclone filter system and consider implementing a more suitable pigging program. The group also recommend taking extensive analysis of the black powder, to access the constituent parts of the powder and understand how black powder is generated and grows on the pipeline wall.

6.1 Cyclone filter

Looking at what has been installed at other terminals, the most common layout is a cyclone separator followed by a filter. Other terminals have both coarse and fine filters in order to optimise the removal process. Since installing two filter stages at the thesis terminal is not a realistic solution, the group suggest replacing the cyclones with cyclone filters. This does not necessarily have to be a major increase in plot-size, since the design footprint is comparable. Before doing this design change, investigating the cost effectiveness of this proposed filtration solution is important, as modification jobs are usually costly affairs.

6.2 Pigging program

During conversations with different pig suppliers, it has emerged that it is a good idea to change the types of pigs being used. Together with vendors who have had success with similar operations, the group suggest a more aggressive and suitable pigging program. The sponsor does not want to increase the frequency of pigging, as this might increase the black powder problem.

Gassco also have sufficient control of corrosion rates in the pipeline. Therefor the conclusion is to not increase the pigging program but use more suitable pigs when the operation is being done, to remove more of the black powder. Research also show that the industry has developed a lot over the last ten years, so the availability of specialist pigs is much larger at this point. This might help achieve the goal of less black powder into the terminal, the next time pigging is done.

Black powder is a complex problem, known in the industry all over the world. It is difficult to estimate the quantity, since all the factors creating black powder is depending on each other. The reservoirs will change over time and may produce more/less CO_2 and H_2S. The efficiency of the TEG contactor can also vary. Therefor the group suggest that extensive analysis of the black powder is performed next time the pipeline is pigged.

Based on discussion with sponsor the mechanism of formation for black powder in pipelines is a subject matter that needs to be further understood.

Understanding the above will increase knowledge about the powder. With this new knowledge new methods may be developed on how to prevent the appearance of black powder, and thus ensure contaminate free gas delivery.

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8. List of Figures

9. List of Tables

10. Attachments

Attachment 1: PFD thesis terminal

Attachment 2: Concentrated lab rapport pipeline