Optimizing flow assurance using pigging in sub-sea pipelines

Master of Science in Engineering by advanced coursework and research:

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DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted to the Degree of Master of Science, in Petroleum Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

...Derek de Wit...

...5th... Day of ...November.....2015

DEDICATION

To my Wife, Bianca de Wit, who has been a source of encouragement and inspiration to me throughout my studies, a very special thank you for providing the love and support through the months of writing. Thank you for all you have done actively to lead me to my full potential.

ABSTRACT

One of the most used techniques for control of wax deposition within subsea pipelines is pigging. The method simply scraps the wax away from the pipe wall using a pig as part of the process. A pig is pushed forward with the natural pressure of the fluid from the reservoir into the pig launching station that is situated at the end reservoir. The force that the pressure creates will force the pig to straight through the transportation pipeline to the pig receiving station where the pig will then get trapped and removed from the pipeline. Pigs are designed with discs and brushes to scrap off all the wax that has precipitated to the inside of the pipe wall. The pig will have bypass holes to allow the scraped off waxes to flow past the pig and dissolve back into the fluid and or stay in front of the pig and will then be drained at the pig receiver to get rid of the build up waxes on the inside of the pipeline. It is therefore critical to find the right pigging frequency by doing calculations in order to reduce the costs and avoid flow problems as the wax layer buildup causes the bulk viscosity of the oil to increase sharply and lead to high pressure losses within the pipelines. Calculations are done taking all the variables into consideration to plot a graph to evaluate the optimum frequency to launch a pig. It is also known that it is almost impossible to launce the pig at its optimum frequency due to production, maintenance etc requirements. This makes it very important to study the frequency graph and to select the best suitable alternative time to launch a pig without wasting money launching the pig to frequent or to ensure that the pig doesn't get launched too late which will end up getting stuck inside the pipe.

This thesis has investigated some of the key criteria to consider when finding the **optimal** pigging frequency strategy such as what is the optimum pigging frequency point, launching a pig to frequent and launching a pig too late it also indicates what should be considered when it's not possible to launch a pig at its optimum frequency point, describing different pigging regions advantages and disadvantages. Some of the advantages will be wax free pipelines, pigs won't get stuck inside of the pipeline, more oil production and some of the disadvantaged will be launching the pig too late means that the pig might get stuck inside the pipeline, loss of production and possible abandonment of an oil well which is very costly.

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SYMBOLS

N	Number of days between pig runs
C_d	Discharge Coefficient (Typically 0.7)
ΔP	Pig Differential Pressure
ρ	Oil density
A_{bypass}	Bypass area
A_{pipe}	Internal area of the pipe
V_{pig}	Pig Velocity
V_{oil}	Oil Velocity
d	Pipeline Internal Diameter
$t_{wax,daily}$	Maximum daily wax deposit
Q_{oil}	Volume flow of oil
Q_{wax}	Volume flow of wax
L	Length of the pipe

ABBREVIATIONS

MFL	Magnetic flux leakage
PIG	Pipe inspection gauge
DP	Differential Pressure
UT	Ultrasonic
ILI	In-line inspection
OHTC	Overall heat transfer coefficient
DSDP	Deep Sea Drilling Program
WAT	Wax Appearance Temperature
AMPL	Automated Pig Launching
ROV	Remotely operated vehicles

1 CHAPTER 1: INTRODUCTION

Subsea pipelines play very significant roles in transporting oil from the exploitation fields to processing plants and customers. Long distance subsea pipelines have been built in the past decades and will continue to be extended due to constant increasing demand, not only for domestic need but also for export. Petroleum exploration and production operations are targeting fields in deep and ultra-deep waters throughout many parts of the world. Figure 1 shows the deep-water basins containing hydrocarbons around the world. The steady increase of oil prices has opened the way for Deep Sea Drilling Program (DSDP) in remote locations across the world (Figure 1). This trend requires a robust understanding and planning of flow assurance in increasingly demanding conditions

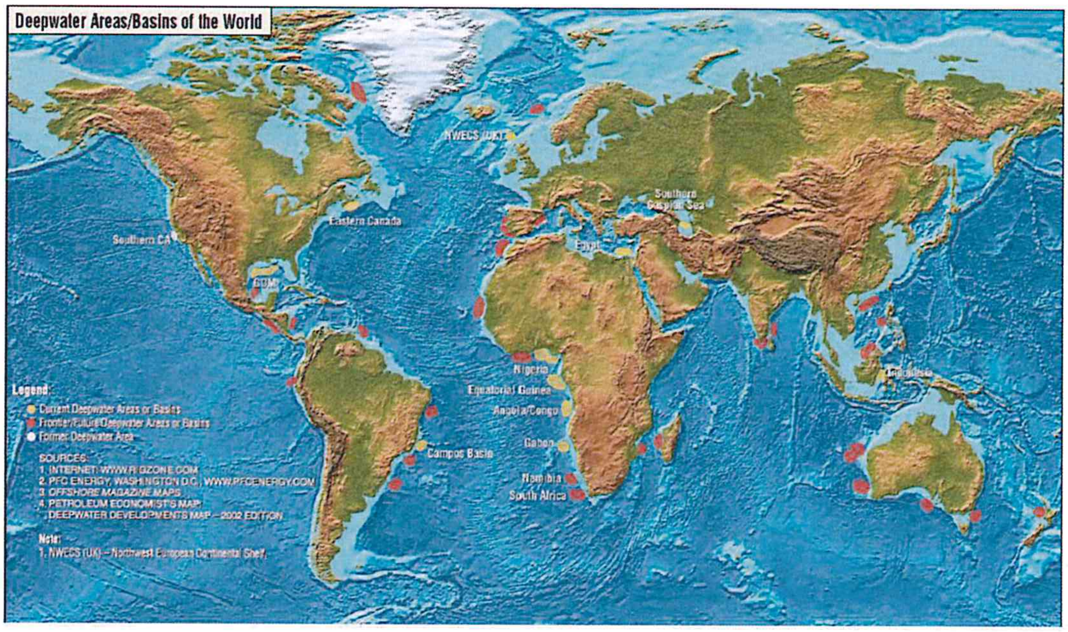

Figure 1. Deepwater basins containing hydrocarbons around the world.

Crude oil is a complex mixture of heavy hydrocarbons which consists of aromatics, paraffin, naphthenic, resins, asphaltenes. In deep sea environment, the temperature of the crude oil is low and these heavy components may precipitate and deposit on the pipe internal wall in the form of a wax-oil gel. The gel deposit consists of wax crystals that trap some amount of oil. As the temperature gets cooler, more wax will precipitate and the thickness of the wax gel will increase, causing gradual solidification of the crude and eventually the oil stop moving inside the offshore pipeline. Crude oil may not be able to be re-mobilized during re-startup. The effective diameter will be reduced with wax deposition, resulting in several problems, for example, higher pressure drop which means additional pumping energy costs, poor oil quality, use of chemical components like precipitation inhibitors or flowing facilitators, equipment failure, risk of leakage, clogging of the ducts and process equipment. It would cost millions of dollars to remediate an offshore pipeline that is blocked by wax. The highest temperature below which the paraffin begins to precipitate as wax crystals is defined as Wax Appearance Temperature (WAT). Below the WAT, crystals may form and be transported with the remaining fluid or deposit on a cold surface, leading to fouling. The pour point is the temperature at which a fluid ceases to pour – the formation of a 3D network spanning the pipe - can occur when flow is interrupted (Carnahan, 1989, Burger et al., 1981)

The wax deposition problems in the interior of production and transportation pipelines have over the years become the single most critical operational challenges faced by the oil industry, as new oil fields are being developed in more remote and cold hostile environments. To cope with this challenge, subsea pipeline engineering need to be optimized both at the engineering and technological levels in order to operate, and maintain these systems economically and guarantee flow assurance.

The objective of this study is to contribute to the building of a coherent strategy to assure a maximum flow assurance of the hydrocarbons in a subsea pipeline by optimizing the pigging frequency and analyzing the frequency of pigging in different field configurations.

2 CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The study of wax deposition in pipelines is a complex subject; its understanding involves many areas of knowledge as are phase transition, thermodynamics, heat transfer, mass transfer, and fluid mechanics, among others. The ability to make accurate predictions of deposition rates of wax inside ducts is of fundamental importance to assist in the stages of production of new fields, as well as in programming interventions for removal of accumulated deposits

Some of the most important factors governing the wax deposition are:

2.1.1 Temperature of the crude oil

Previous experimental works have shown the temperature dependence of wax containing crude oil (Hoffmann and Amundsen, 2010) When the crude oil is above a certain temperature, it behaves as a Newtonian fluid. However, when the temperature decreases, non-Newtonian rheological behaviors may appear (Barry, 1971). The wax deposition problems occur when the temperature of the crude oil decreases below the WAT. The WAT is different for each crude oil. The concentrations of light ends in the crude oil have a significant effect on the WAT, because they act as a solvent for the wax in the crude oil. The light ends are light hydrocarbons, such as methane and ethane, and other gases, such as CO_2 and N_2 (Carnahan, 1989). A decrease in the light ends can thereby reduce the solubility of the wax in the crude oil, resulting in an increase in the WAT.

In deep water flow lines the temperature is usually low, and if the distance from the reservoir to the process facilities is long, the cold seawater will eventually start to cool the well stream flow, leading to wax precipitation inside the flow line walls (Misra et al., 1995). To restore the flow of the crude oil a high pressure must be applied to break the gel. However sometimes the pressure needed to resume the flow is not great enough, leaving the pipeline chocked. As shown in Figure 2 the temperature gradient between the cold tubing/pipe wall ($T_{wallout}$) and the bulk oil (T_{oil}) initiates a concentration gradient in the wax molecule distribution. Wax molecules near the pipe wall crystallize out of the oil as wall temperature falls below WAT.

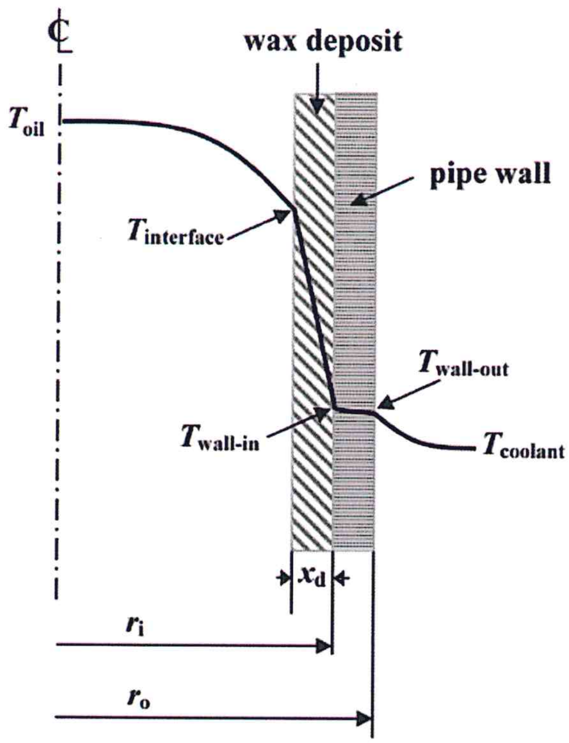

Figure 2. Different temperatures across various thermal resistances during wax deposition in a pipe (Huang et al., 2011)

2.1.2 The flow rate of the crude oil

The flow rate of the crude oil within the pipelines may affect the cooling rate of the crude oil as it flows and may also affect the shear stress Venkatesan et al (2005). When the wax begins to crystallize this will result in higher viscosity of the crude oil and loss of the pressure in the pipeline, which can reduce the effective capacity of the line. A high viscosity and wax deposition in the flow lines will require a higher pumping pressure to ensure flow of the crude oil.

Mohammed (2007) has also shown that a higher flow shear, which is a function of flow rate, leads to lesser but likely harder deposit build-up. Thus wax deposition gradually decreases with increase in flow rate and turbulence. The increase of flow rate, decreases the amount of wax deposited or entrapped oil in the deposited wax thus leaving only harder and more compact deposits. Lund (1998) has reported that a low flow rates affect wax deposit mainly because of the longer residence time of the oil in the tubing.

The capacity of predicting the phenomenon of paraffin deposition in the walls of the ducts depends crucially on understanding the physical mechanisms governing the deposition. According to the work of Burger et al. (1981) the possible deposition mechanisms were identified as the molecular diffusion, Brownian diffusion, shear dispersion, and deposition by gravitational effects. In addition to Burger et al. (1981), others pioneering studies are Brown et al. (1993), Svendsen (1993), Azevedo and Teixeira (2003), conducted research in this direction.

The present work aims at performing a numerical simulation of the deposition of paraffin in submarine pipelines considering the two main mechanisms in literature; deposition by molecular diffusion and shear dispersion. The molecular diffusion occurs due to temperature gradient generated in the radial direction of the duct, this caused by the difference between the duct wall temperature and oil flowing inside. Because the solubility of paraffin decreases with temperature, the temperature gradient set, generates a higher concentration of paraffin dissolved in the warmest region which leads to a transport by molecular diffusion in the liquid paraffin into the wall of the duct. The dispersion of shear is also a mechanism that contributes to the deposition of paraffin, where small crystals contained in the oil tend to move in the direction of the flow. However, as the flow velocity is maximum at the centre of the tube and zero on the walls, there is a shear that induces motion of the particles, known as shear dispersion. This movement may be responsible for transporting the paraffin precipitated from the fluid in the centre of the line towards the wall, where are joined to the existing wax deposits due to the phenomenon of molecular diffusion.

2.2 Wax Deposition

Lund (1998) and Matzain (1999) have shown that the precipitation of paraffin or wax occurs when the wall temperature of a pipe through which paraffinic oil is transported falls below the Wax Appearance Temperature, WAT (also called cloud point). Although Burger et al. (1981) identified four possible mechanisms for paraffin deposition: molecular diffusion, shear dispersion, Brownian diffusion and gravity settling, it was shown that gravity settling has no impact on the deposition process and that Brownian dispersion may be neglected. Several investigators Burger et al. (1981) and Brown et al. (1993) suggested that molecular diffusion is the primary mechanism for wax deposition. We will discuss the molecular diffusion and the shear dispersion mechanisms.

2.2.1 Molecular diffusion mechanism:

The molecular diffusion is the main driving mechanism of the growth of the wax deposit as reported in current literature (Burger et al.,1981 and Brown et al., 1993) . It has been shown that the existence of a gradient of concentration of dissolved paraffin in the crude oil generates the molecular diffusion automatically as the crude transported in the pipeline is cooled by the external thermal environment. The solubility of paraffin molecules is highly dependent on the fluid temperature; therefore, whenever there is a radial temperature gradient in the pipe, a radial concentration gradient will also develop. This concentration gradient is the driving force for the dissolved paraffin molecules to be transported towards the pipe wall where the dissolved wax concentration is lower.

As mentioned above the wax solubility is a decreasing function of the temperature, therefore any variation in the crude oil temperature generates a gradient of dissolved wax concentration. The oil close to the wall of the pipeline will be colder than that the fluid in the centre of the pipe. So one will have more dissolved wax in the middle of the pipeline than close to the wall. To compensate for this deficit, the system (crude oil + dissolved wax) to tend to balance the system by moving more wax from the centre of the tubing towards the wall where the wax deposit occurs. The wax starts to precipitate when the temperature of the pipeline surface becomes lower than the WAT of the crude oil. The molecular diffusion mechanism has widely been accepted as the dominant wax deposition mechanism.

To quantify the flow of migration of wax the first law of Fick is used:

$$\frac{dm_m}{dt} = \rho_d A D_m \frac{dC_l}{dr} \qquad (2.1)$$

Where;

ρ_d : Volume mass of the deposit

D_m: Diffusion coefficient of crude oil

A: deposit area

Singh et al. (2000) proposes a modified form including the molecular diffusion of dissolved wax inside the deposit. Due to its crystal network structure, wax deposits behave as a porous medium in which wax molecules continue to diffuse due to the radial gradient of temperature across the deposit. They hypothesized that a counter diffusion phenomenon takes place at the deposit interface, where wax molecules diffuse into the crystal network, displacing the oil trapped in the deposit interstices, which causes an increase in the deposit wax content, e.g. aging. Singh et al. modeled the deposit growth as the radial convective flux of molecules from the bulk to the fluid deposit interface minus the diffusive flux into the gel interface. This last term was modeled using Fick's law (Eq. 1) with an effective diffusion coefficient for the mass transfer of wax molecules inside the deposit.

The Fick equation governs this diffusion and therefore equation (1) becomes:

$$\frac{dm_m}{dt} = \rho_d A D_e \left.\frac{dC_l}{dr}\right|_{wall} \qquad (2.2)$$

$$D_e = \frac{D_m}{1+\alpha^2 \frac{F_w^2}{1-F_w}} \qquad (2.3)$$

F_w and α are respectively the mass fraction of solid paraffin in the deposit and the report/ratio of average aspect of the paraffin crystals. The widely recognized transport methods contributing to wax thickness on the pipe wall are molecular diffusion of dissolved wax, particle transport of precipitated wax, and sloughing of previously deposited wax.

2.2.2 Shear dispersion mechanism

The shear dispersion mechanism takes into account the fact that the bulk fluid will often have a higher velocity compared to the fluid near the pipe wall, due to the friction between the fluid and the wall. Already precipitated wax near the pipe wall will therefore move to the pipe wall where the velocity are lower and deposit. For instance high shear environment, found in turbulent flow, are likely to disrupt the adhering and growing of wax deposits on the pipe wall. While low shear environment, laminar flow, will cause the wax molecules to easily adhere to the pipe wall, and cluster together (Lira et al, 1996). Shear dispersion occurs when the wax particles move across fluid streamlines due to differences in shear imparted by other flowing particles. The particles in solution rotate as they flow, and due to the viscosity of the fluid the rotating particles will impart a shear force on nearby particles. Shear dispersion is considered to be one of the major mechanisms in wax deposition and appears to play a bigger role at lower temperatures as well as lower heat fluxes (Brown et al, 1993); hearing of the wax molecules occurs due to the hydrodynamic drag of the flowing fluid and depends mostly on the flowrate and viscosity of the fluid. Higher viscosity and low flowrate result in high wax deposition rates. However, in highly turbulent flow, deposition rates decrease with increased flow as wax is mechanically sheared off the deposits on the pipe wall. As the deposit thickness increases, so does the shear rate due to the decrease in the flow area and increase in flow velocity. This increase in shear rate causes an increase in the shear stress on wax molecules and formed wax crystals which serves to diminish the overall wax deposition rate (Burger et al, 1981).

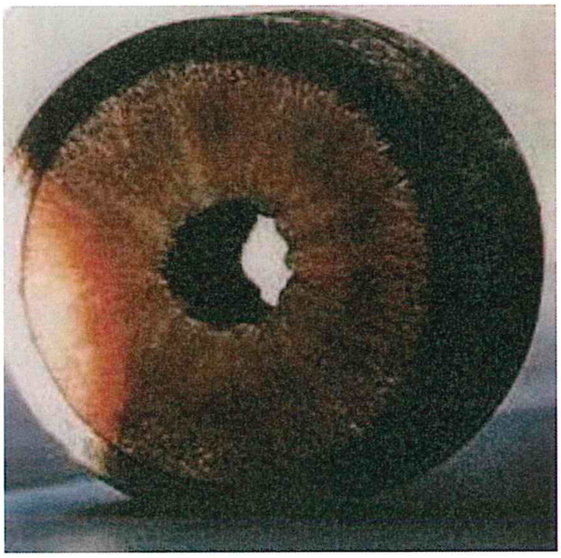

Figure 3: Example of wax deposition in a pipe.

2.3 Flow assurance

Treatments of the wax problem usually fall into four categories: (1) mechanical; (2) thermal, usually involving hot fluids, although sometimes maintaining higher pressure in flow lines and/or thermal insulation of tubular goods to maintain tubing temperature above the cloud point is beneficial; (3) chemical, including the use of solvents, wax crystal modifiers, and paraffin dispersers; and (4) combinations of the above. In addition to the above treatments, the oil transportation may be operated in such a way as to minimize paraffin problems. Removal of wax from flow lines can account for significant additional operating costs. The operating conditions that allow waxes to precipitate in a pipeline must be identified and deposition rates must be estimated, so that remedial efforts can be evaluated and selected and the costs associated with the removal of wax deposits may be determined. Flow assurance is an activity performed to ensure the required flow of crude oil reaches the topside processing and/or customer by analyzing the following aspects:

- Wax
- Hydrates
- Slugging-
- corrosion

Some of the typical flow assurance problems:

- Build-up of deposits of asphaltenes, wax, inorganic scale, or sand (or a mixture of these)
- Formation of hydrate plugs
- Occurrence of unacceptable flow regimes, such as severe slugging or erosional velocities
- sludges, naphtenates
- Corrosion phenomena induced by water settling and low velocities

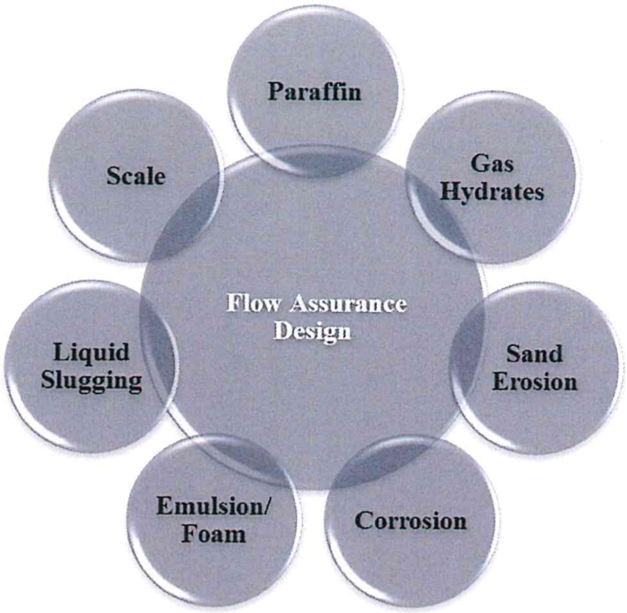

Figure 4: Flow assurance design issues.

Flow assurance has become a huge part of the modern day production due to the increase in the markets demand for fuel and by products. A large amount of produced oil goes through long distance subsea pipelines which may cause flow assurance challenges such as paraffin wax deposition/precipitation, hydrates, inorganic scale accumulation. These Precipitation and deposition can lead to major issues in forms of plugged pipes and production losses leading to reduced flow area and pressure drop in the pipeline. It is therefore important to address these issues from an operational point of view.

A great amount of effort has been and is being given to finding methods of eliminating wax issues in pipelines (Newberry et al., 1986). Primarily, the most successful and reliable means of dealing with wax is mechanical removal of deposits through pigging.

Pigging allows wax to deposit on the wall and build up a wax layer before it gets scraped off. The frequency can vary from days up to months. It is important to find the right pigging frequency to reduce the costs and avoid flow problems as the wax layer builds up, the more challenging it becomes to pig the pipeline. The wax thickness should be assessed to evaluate efficiency of pigging.

The biggest challenge has been to determine which criteria to pay attention to in order to find the optimal pigging frequency. Although it is obvious from an operational perspective that pigging operations should happen at a given frequency to prevent wax from hardening.

2.4 Pigging and Equipment

Pigging has been used for many years to clean large bore piping in the oil production industry, but these days it is very common to use pigging in smaller bore pipelines because of its ability to increase the efficiency of the process and increase in production.

Pigging is the most common method used for the removal of buildup waxes in the pipeline not only because it is reliable but also because it cleans the inner surface of the pipeline as well as to make use of intelligent pigs could give you crucial information of the pipelines condition and one is able to track the pig. (Lino et al, 1995) carried out experiments on pigging of paraffin deposits. They investigated wax shear strength by compressing wax sample between two plates. They found that the maximum measured value of the compression force is the minimum force required to cause plastic deformation to the wax sample, and hence it corresponds to the minimum level of stress required to remove the wax deposit. From this work simple approach was presented to estimate the minimum pressure on pigs below which wax removal does not occur. Further experiments on the mechanics of wax removal were conducted by (Wang and Sarica, 2000).Different types of pigs were pulled through a cast wax pipe. Wax thickness, oil content, pig type and pigging efficiency were investigated. The pigging force was divided into three parts; base line force, breaking force and wax plug transportation force. The base line force is the force required to move pig in a clean pipe, which varies with pig types and pig oversize. The breaking force, similar with wax shear strength tested by Souza, is the force that causes plastic deformation of the wax layer, which depends on wax thickness, wax properties and pig type. The wax plug transportation force is the force required to move the wax plug cut off from the pipe wall out of the pipe. (Hovden et al, (2004) modeled the pigging procedure based on the findings in Wang and Sarica's study.

The pigging technology and design used varies with the process requirements (Pople, 2003). Additional assessment are also conducted such as corrosion and surface pitting, cracking and defects on the welds in steel pipelines using magnetic flux leakage (MFL) pigs. Other intelligent pigs use electromagnetic acoustic transducers to detect pipe defects. The use of the caliper pigs in pipelines help to measure the roundness of the pipeline and therefore determine whether there are areas of crushing or other deformations.

Although the use of pigs does not require production to stop, (better flow assurance) , one needs to ensure that the pig is launched at the right time when wax thickness has not exceeded the maximum thickness in order to avoid that the pig can get stuck inside the pipe and cause a total production shut down.. Below is some of the existing rule-of-thumbs being used today:

- To launch a pig after 2mm (0.078") of wax had built up in the line or after 50 barrels of wax gathers.
- Limiting pressure drop across the pig to 50-100 psi.
- Limiting total wax thickness to 10% of the cross-sectional area.

One should note that it is very dangerous to use pigging and pig programs incorrectly. If one uses these programs incorrectly it can lead to the plugging of pigs in the pipelines resulting in an expensive cutout and costly downtime. Since the pigs need to push wax further and further in longer well step outs and greater export distances it has become one of the latest challenges being faced with the launching of the pig. Solutions et al., (2006), stated that there are numerous inspection techniques and technologies that are used to monitor the pipelines condition and integrity. One of the most important objectives of pipeline inspection is usually to assess corrosion-caused metal loss. Inspection also provides information on dents and other damage that may eventually cause failure and leaks. Internal inspection will also be carried out by making use of pigs that provides and perform a variety of functions.

Pharris and Kolpa (2007) report that a large amount of equipment is required to introduce the pig into the pipeline and to retrieve the pig at the end of the segment being pigged. A launcher is required at the upstream end of the section, and a receiver is required at the downstream end (Figure 5). The distance between these pig "traps" is depended not only on the service and location of pump or compressor stations and operating procedures but also the material used in the pig. For more than one reason when a pig was launched it must be retrieved first from the mainline pipe before the pipe reaches the next pump station. Most of the time, launching and recovery facilities are collocated at pump stations.

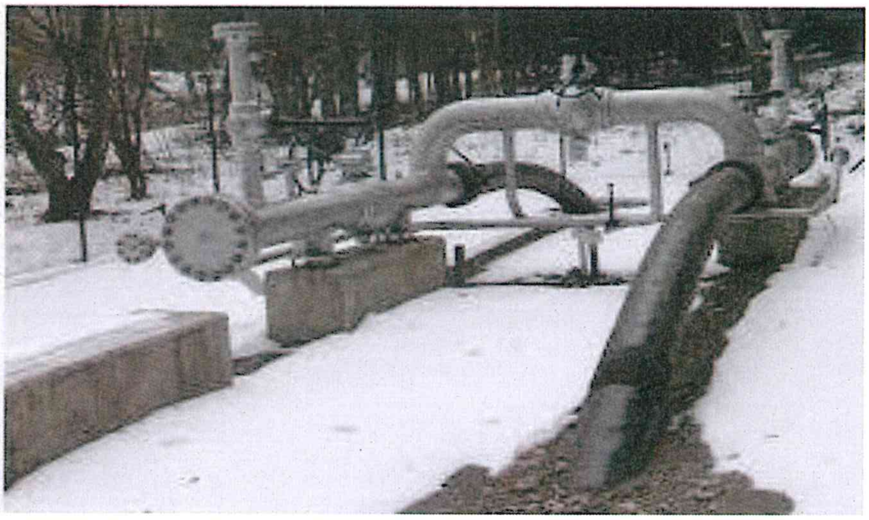

Figure 5: Pigging station

2.4.1 Pigging Station

The operation of the launching of the pig involves to clean, inspect and also to do a general integrity check (such as checking the pipelines wall thickness). So far this kind of inspection method is the most reliable and comprehensive one for subsea pipelines. Below is the general procedure together with steps to describe the pigging operation (Table 1 and Figures 6-14).

Table 1: HKCG's Procedure for launching and receiving of a pig (HKCG, 2010)

Step	Description
1	Nitrogen gets injected into the pig launcher after it has been confirmed that the isolation valve has been closed to remove any residual town gas inside the pig launcher. This step is to make sure that the pig launcher is free of any gasses when the pig launcher is opened in next step (Figure 8).
2	Now that the pig launcher is free of any gases, the pig launcher is opened up. A (PIG) gage is inserted into the pig launcher (Figure 9).

3	This pig then gets inserted into the pig launcher after inspection, the door then gets closed and the pig launcher the gets purged with inert gas. The isolation valve for the pig launcher and behind the pig is opened. The pig launcher will now get filled with process. The process flow will carry pig to pass through the submarine gas pipelines upon the open of another isolation valve of the pig launcher (Figure 10).
4	The PIG then arrives at the other end of the pipeline at where a pigging station is designed for receiving the PIG called the receiver (Figure 11).
5	Nitrogen is injected into the pig receiver after the isolation valve has been closed to remove any residual town gas inside the pig launcher. This is making absolutely sure that the pig receiver is gas free before it is opened (Figure 12).
6	Now that the pig receiver is free of any gases, the pig receiver is opened up. A (PIG) gage gets taken out of the pig receiver (Figure 13).
7	All the isolation valves will then be closed to make sure that the receiver is fully isolated from the main process during normal operation (Figure 14).

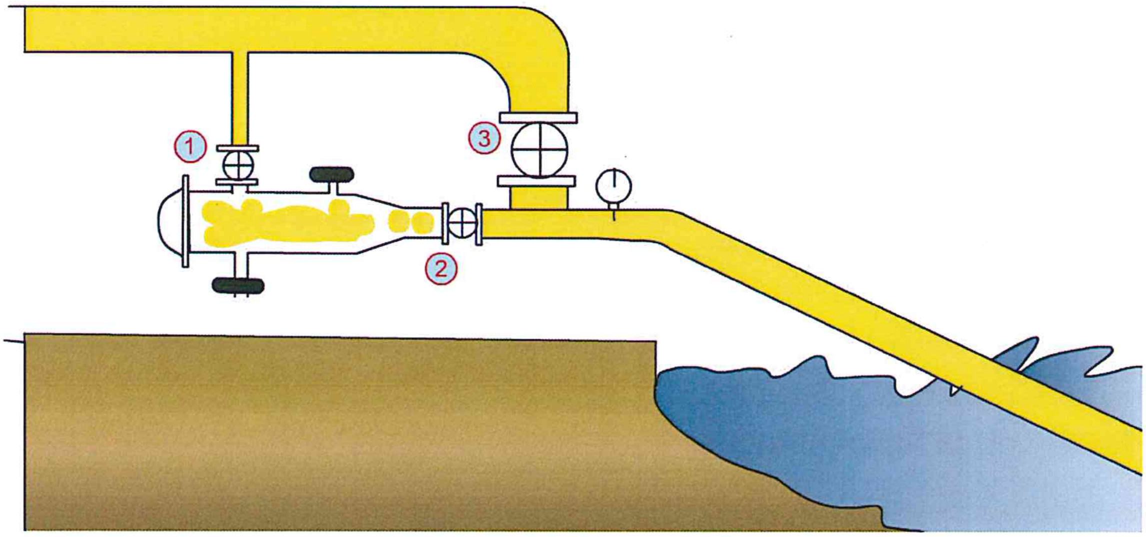

Figure 6: Setup of the Pigging Operation.

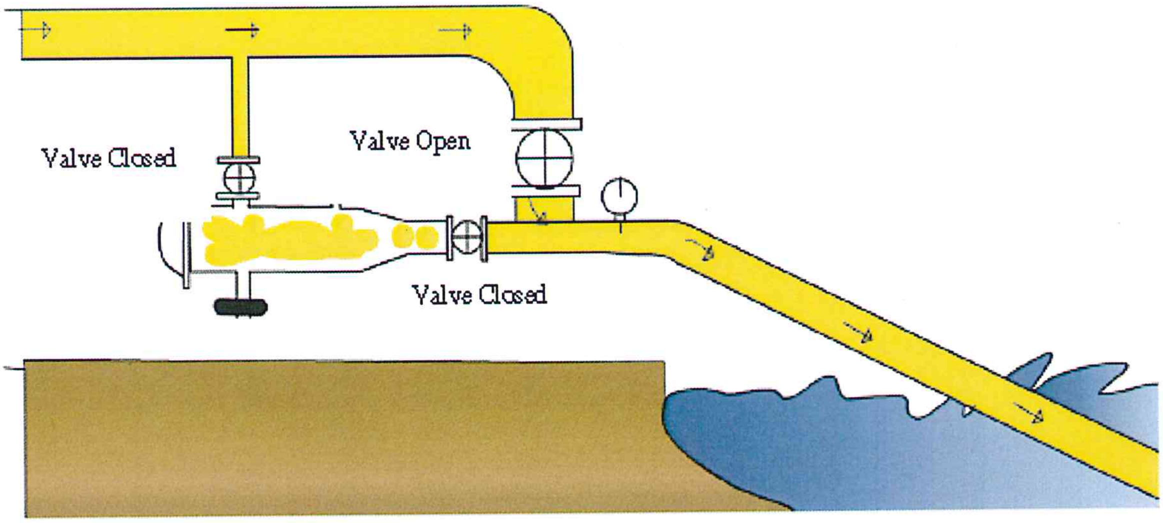

Figure 7: Town gas flows from pigging station to the submarine gas pipeline (as shown by arrows) under normal situation, pig launcher and pig receiver are isolated from the town gas transmission system

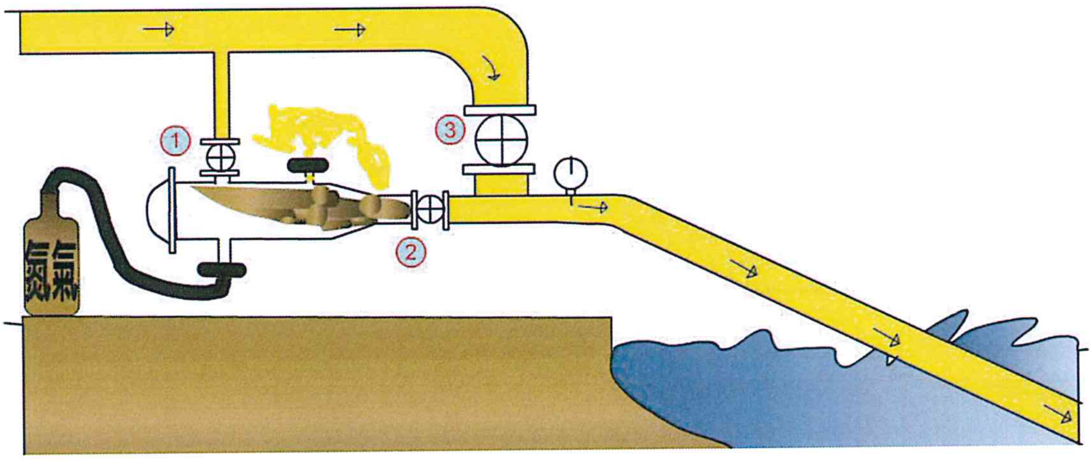

Figure 8: Step 1, Use an inert gas (Nitrogen) to remove residual gas inside the pig launcher

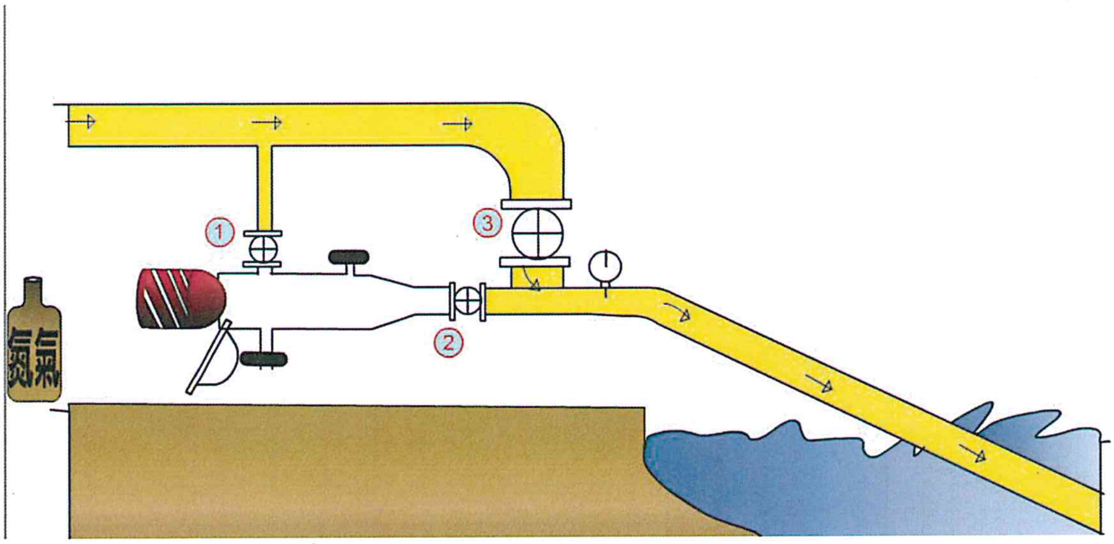

Figure 9: Step 2, Open up the pig launcher and insert the pig

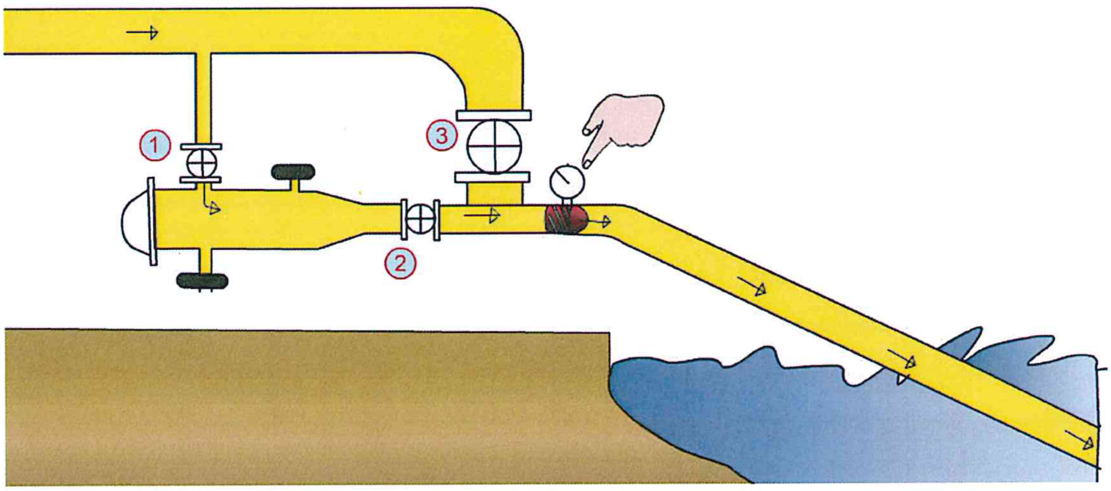

Figure 10: Step 3, Use town gas flow to carry the pig into the submarine gas pipelines

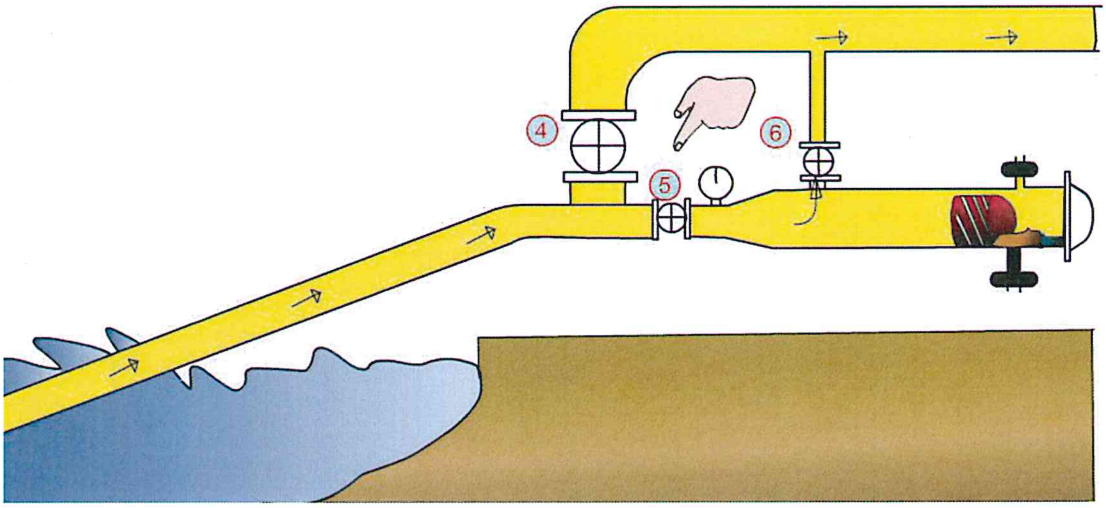

Figure 11: Step 4, Pig arrives at the other end of the submarine gas pipeline at where a pigging station is designed for receiving the Pig.

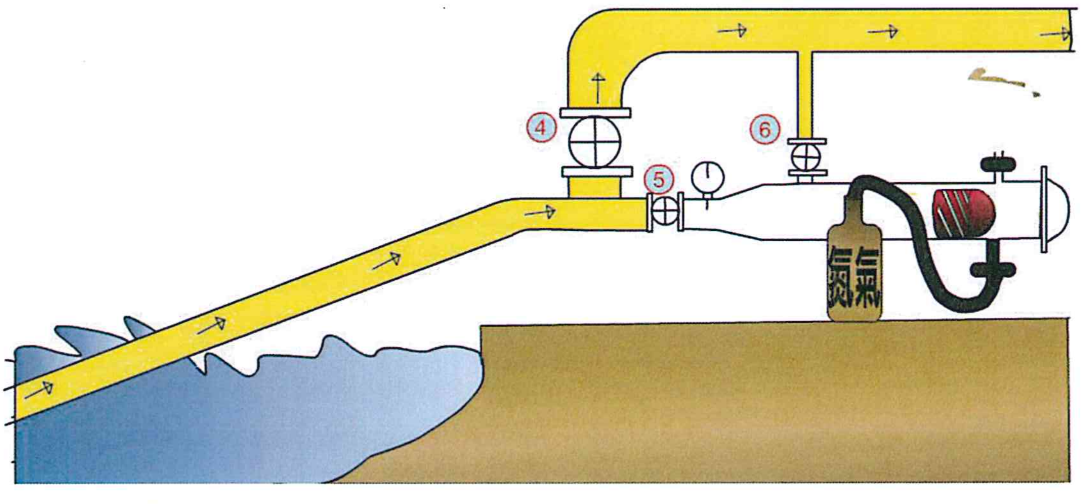

Figure 12: Step 5, Use inert gas (Nitrogen) to remove residual gas inside the pig receiver

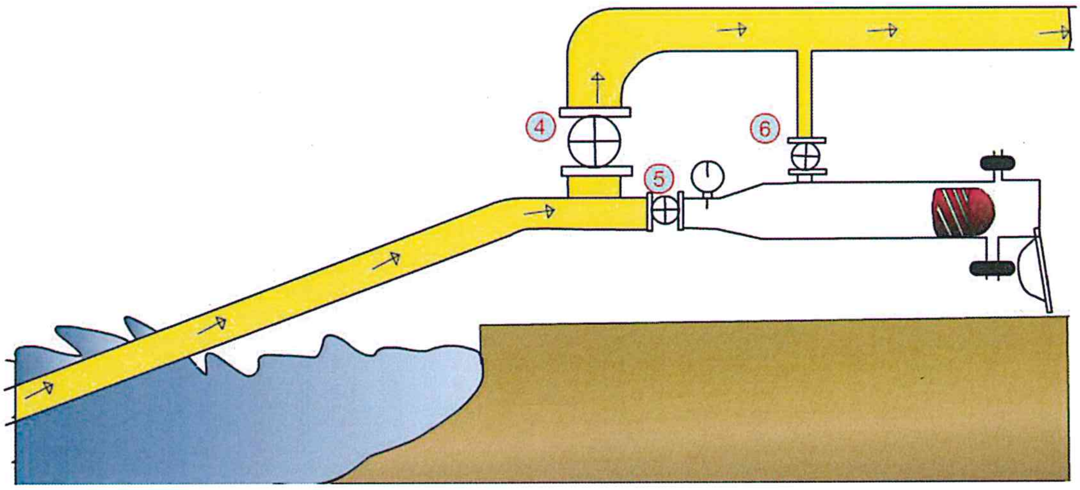

Figure 13: Step 6, Open up the pig receiver and take out the pig

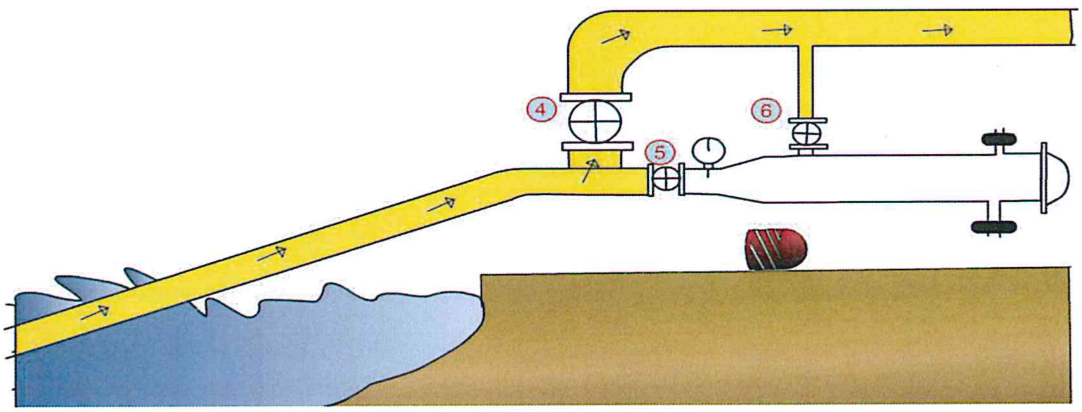

Figure 14: Step 6, the pipe receiver will be isolated from the gas pipeline during normal situation.

2.5 Alternative Flow Assurance Methods

2.5.1 Insulation

Insulation is a very good method used in the industry to ensure good flow assurance of hydrocarbons. Depending on the application and conditions surrounding the pipeline different insulation types will be used. Hunter, (2008).The most common types of insulation being used in the industry today is pipe-in-pipe, wet insulated pipe and flexible pipe insulation.

Pipe-in-pipe insulation generally is used to protect the production pipeline during handling and placement. So this means that a material with a low strength and high in insulating can be used.

Wet insulated pipe is where the pipe is directly coated with syntactic foam material and placed on the sea bed generally without any other protection or cover. This syntactic foam composite reduces thermal conductivity of the pipe as well as reduces the weight of the of the pipe coating.

Flexible pipe material is an extruded polypropylene thermoplastic mixed with low glass microspheres material that gets wrapped around the pipe. This is a very good insulation for consistent flow assurance up to 3000m.

The biggest disadvantage of insulation is that it is only suitable for depths between 5km-10km and still have a relatively good/guaranteed flow assurance Akpabio (2012).

2.5.2 Chemical cleaning

To remove the built up of these waxes chemical cleaning is also a preferred method used in the industry today. According to Mokhatab (2009) when solvents, pour-point dispersants and microbial products are pumped into the process line so that the wax bonds with the solvents, pour-point dispersants and microbial products to clean the inside surface of the pipe from the wax bonds.

It does come with a very big challenge that needs a lot of consideration when choosing solvents, pour-point dispersants or microbial products because it can damage the chemical seals on pumps or mechanical equipment, gaskets between flanges and also seats of the valves when using the wrong chemical to clean a pipeline.

Another problem that has been picked up according to research that was done is that chemical cleaning can only be used with crudes that have certain characteristics Kjoraas (2012). That is why pigging is still the preferred because there is no difficult matrix to consider when choosing your pig.

3 CHAPTER 3: MATHEMATICAL MODEL BUILDING

3.1 Problem Statement

Demand and supply of oil in the world have increased dramatically over the past 3 decades and with the recent emergence of countries like China and India on the global stage the world is struggling to meet the ever-increasing demand for oil. On the other side; many of largest oil fields are reaching a maturity stage after decades of high productivity. As a result, oil companies are exploring new oil fields situated in deeper water, where most of time the wellbore temperature may be very low.

These changes of the operating temperature-pressure equilibrium conditions of the crude oil often result in a phenomenon known as wax deposition-precipitation whereby the wax (an important component of crude oil constituted of saturated hydrocarbons and mainly of long-chain n-alkan with 20-50 carbon atoms) precipitate on the tubing and flow lines of production and transportation system facilities. The problem of wax deposition has plagued the petroleum industry for decades and can lead to major issues in forms of plugged pipes and production losses leading to reduced flow area and pressure drop in the pipelines.

It is therefore important to address these issues as they have a significant impact on the operation (restricted flow due to reduced inner diameter in pipelines, increased wall roughness, increased viscosity of the oil) but also on the economy of the production system (reduced capacity and production).

The main drives used for this study was to determine the optimum frequency that was considered and looked are as follows:

- Wax deposition.
- Flow temperature.
- Quality of the oil.
- Length of the pipe.
- Costing of crude oils.
- Cost to un-block a blocked pipe.
- Lost in production due to a blocked pipe

After all these concepts are clearly defined one case studies will be compared and discussed in chapter 4 to prove the statement of bypass pigging and to find the best optimized pigging frequency.

3.1.1 Wax deposition

Oil that comes very close to the wall region is cooled below the WAT. The deposition, or gelation, is a result of flocculation of orthorhombic wax crystallites that starts to appear in the fluid during cooling, these precipitated wax crystals then starts to forming a network. The deposited gelation does not consist of pure solidified paraffins, but is rather a wax oil mixture containing a large fraction of oil trapped in a 3-D network of wax crystals (Singh et al., 2000).

The four following steps describe the process of wax deposition (Huang, 2011):

1. Formation of an incipient layer of deposit on the cold pipe wall surface.
2. Radial mass flux of paraffin molecules from the bulk fluid towards the oil/deposit interface (A).
3. Radial flux of paraffin molecules from the surface of the deposit into the deposit layer (B).
4. Precipitation of paraffin molecules inside the deposit resulting in increased solid wax content. The growth rate of the deposit is determined by the difference in radial flux from the bulk to the oil/deposit interface (flux A) and the flux from the interface and into the deposit (flux B) as illustrated in Figure 21.

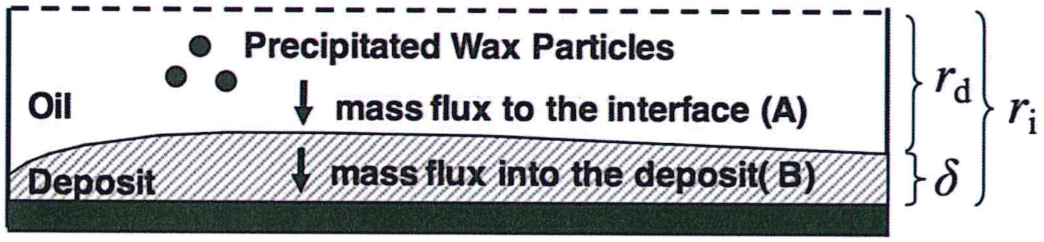

Figure 15: An illustration of the principles of wax deposition by molecular diffusion. The dashed line is representing centerline of pipe and the thicker line representing the pipe wall (Huang, 2011).

The driving force for deposition is the radial concentration gradient causing a mass flux of wax molecules towards the inner pipe wall (Venkatesan, 2004). As the concentration gradient is inferred from the temperature gradient, the temperature profile in the pipeline is required when performing wax deposit simulations. The radial concentration gradient is referred to as the mass driving force for wax deposition and the temperature radial gradient, or difference, is referred to as the thermal driving force (Huang, 2011).

3.1.2 Flow temperature

(Pharris and Kolpa, 2007) The capacity of a pipeline is affected by temperature directly and indirectly. When liquids are compressed one will experience an increase in temperature that then also cause an increase in volume. Thus, the operating temperature of a pipeline will affect its throughput capacity. The throughput capacity can also be affected if you lower the temperature and will the result in the increase of viscosity. If there is an increase in the viscosity of the liquid it will cause more friction along the inner walls of the pipe, requiring more energy to transport the liquid.

In the case where the liquid is a crude oil it is not only the viscosity that plays a role but other solids that also need to be considered in transportation. These solids are typically something like paraffins and asphaltenes that are present in the crude oil that solidifies and becomes a wax that adhere to the pipe wall.

The wax on the inside wall causes a decrease in the inside diameter of the process pipeline and if not scraped or clean properly it could end up blocking the complete production pipeline and could potentially cost a major loss to the production company.

3.1.3 Quality of the crude oil

Over the past few years the number and different types of crude oils that are traded on the international market has steadily increased, partly as a response to diversify sources of supply, and partly because increasing global demand as shown in Appendix A has encouraged production in less well known oil-producing areas. At the moment more than 150 different crude grades are described in The International Crude Oil Market Handbook (2004).

According to (Today in Energy, 2012) light crude oils (lower density or higher degrees of API gravity) and sweet (low sulfur content) are usually priced higher than heavy, sour crude oils. The reasons for this is because gasoline and diesel fuel, which typically sell at a significant premium to residual fuel oil, can be produced much easier and cheaper using light, sweet crude oil. The light sweet grades are desirable because they can be processed with far less sophisticated and energy intensive processes/refineries.

3.1.4 Wax deposition throughout the length of the pipe

Based on the assumptions presented Fick's law is applied to determine the mass transfer rate in a binary mixture of wax and oil (Burger et al., 1981; Azevedo and Teixeira, 2003; Sarica and Volk, 2004; Lee, 2008; Benall et al., 2008; Aiyejina, 2011; Mirazizi et al., 2012):

$$\frac{dm}{dt} = -\rho_{\omega} W_{\omega o} A_i \frac{dC}{dr}\int_i \quad \ldots\ldots\ldots\ldots\ldots\ldots(3.1.4.1)$$

Where: dm/dt (kg/s) is the mass rate of wax transfer in oil, ρ_{ω} (kg/m3) is the density of solid wax, $D_{\omega o}$ (m2/s) is the diffusion coefficient of wax in oil, A_i (m2) is the surface area at which the deposition occurs, C (volume fraction) is the concentration of wax in oil, and r (m) is the radial coordinate at the point of interest measured from the centerline of the pipe. The radial concentration gradient, dC/dr is evaluated at the solid/liquid interface.

Since the density of wax is assumed equal to the density of oil, the weight percent of wax in solution corresponds to the volume percent of wax in solution. The interface area available for deposition, A_i, can be calculated as:

$$A_i = 2\,\pi\, r\, L \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1.4.2)$$

Where: r (m) is the radial coordinate of interest and L (m) is the length of the pipe. If there is no wax deposit at the place of interest, the solid/liquid interface radius equals the inner pipe radius, $r(t) = r_i$. If deposition has occurred, the solid/liquid interface equals the inner pipe radius minus the deposit thickness, $r(t) = r_i - \delta(t)$. The deposit thickness, δ (m), is found by integration of Equation (3.1.4.3):

$$\delta(t) = -D_{\omega o}\frac{dC}{dr}\int_i t \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1.4.3)$$

Where: δ(t) (m) is the deposit thickness at the time of interest, $D_{\omega o}$ (m^2/s) is the binary diffusion coefficient of wax in oil and dC/dr (unit) is the radial concentration gradient at the solid/liquid interface. As the driving force for deposition is found to change with time, the deposit thickness will be calculated as:

$$\delta(t+\Delta t)=\delta(t)+\left(-D_{\omega o}\frac{dC}{dr}\int_{i}\Delta t\right)\text{........(3.1.4.4)}$$

Where: δ(t) (m) is the deposit thickness in the previous time step and Δt (s) is the time step.

3.1.5 Crude oil costs

Figure 22 shows the crude oil price for the last couple of years up until 2014. From this data one can clearly see the oscillation in the oil price and if one compares it with the demand and supply one can clearly see that when supply couldn't meet the demand the price of oil increased.

This is one of the crucial reasons that why flow assurance should be optimize so that there could be some sort of guarantee from the suppliers to the market to prevent a huge increase in price and much more important to prevent avoid a lack of supplying to the market. Dr. E Yardeni (2014)

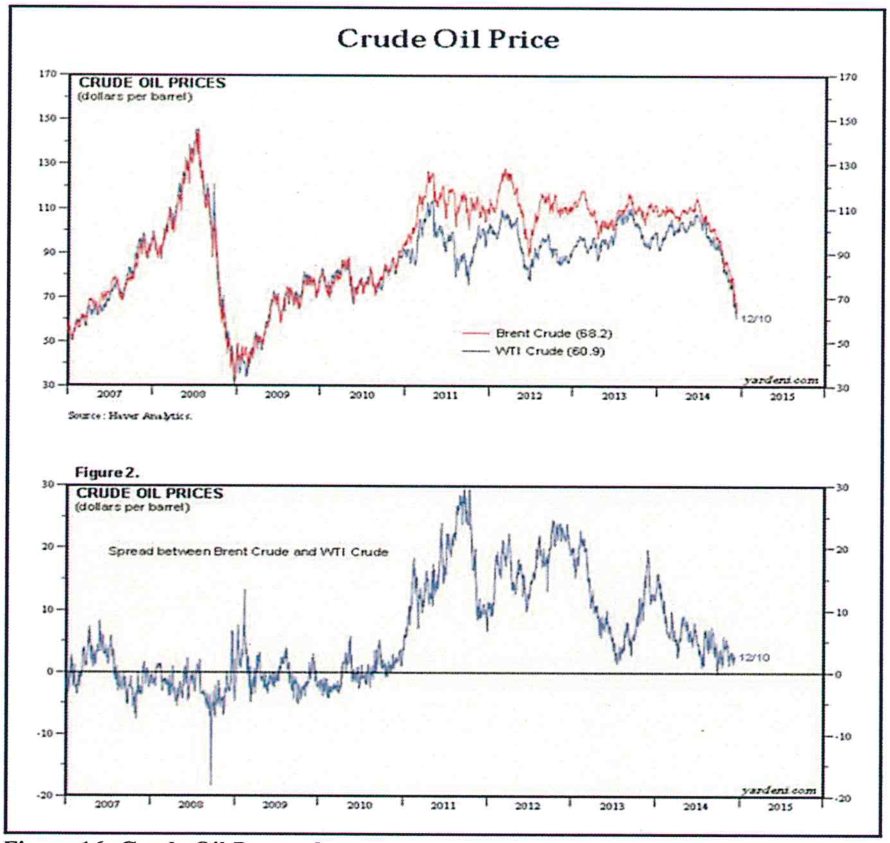

Figure 16: Crude Oil Demand

3.1.6 Price to clean a blocked pipeline

There have been a couple of successful tests done over the years in unblocking blocked pipes in subsea pipelines were pipe-pulse were one of the latest methods used. The reason why pipe-pulse is one of the preferred methods to use is because it removes the need for traditional physical interventions such as drivers. It can be connected to either the pig launcher or an umbilical termination unit; the pipe-pulse does not make use of any physical interaction into the pipeline but instead makes use of a remote method, delivering pressure pulses that are high in energy and volume into the pipeline or subsea umbilical.

Offshore technology (2012) Pipe pulse was used to clean one of Shell UK multiphase flow lines that were blocked with sand and wax for over 11 years. The total cost to unblock the North Sea pipelines was estimated to be around $250,000 (R 2,889,450).

This goes to show that not only did it cost $250,000 to unblock the pipe but a total loss of production for more than 11 years. This is much more expensive than to launch a pig.

3.1.7 Pigging as a cost effective option.

Modern day's technology of a pig launcher and receiver makes it very easy for production companies because of the fact that production doesn't need to stop when pigging the system. The pig simply gets launched into the pipeline with the forces from the crude oil that acts onto the pig as described in section 2.3.

Installation and fabrication costs of the additional piping for the pig launcher and receiver required. Additional to that is the cost of the pig/pigs required for the process depending on the option taken from the oil production company that can vary anything from $25,000 to $35,000 (R327,109.53 to R457,953.34). Then another costing factor that needs to be taken into consideration is the cost of loading the pig launcher with an ROV (Remotely operated vehicles) that can also cost up to $100,000 (R1,308,438.12) including training etc (G. Mitchell, 2013). This is all part of a choice that needs to be made by the productions company and will be explained in section 3.2.2. When these systems are in place and managed properly the following benefits could be gathered using pigging:

- Minimal access is required to the pipeline to launch a pig.
- Minimal manpower is required for pigging operations.
- Using a pig launcher and receiver significantly reduces the cost of pigging.
- To automize the process, pigs can also be launched remotely.
- AMPL greatly reduces the potential for accidents for personnel operating the pig station.
- Pig station modifications are not normally required to use AMPL.
- No external power is required to launch the pigs.
- AMPL provides health, safety and environmental benefits.

Looking at all the benefits of having a pig launcher, receiver and the fact that it is part of the operating methodology will mean that the only cost impact will be with the initial modifications required to the existing pipeline and the pig itself. This is a lot less compared to having to clean a blocked pipeline. The fact of less manpower also adds to the cost saving of the process as well as a smaller chance of human error when automated.

3.2 Modeling Method

3.2.1 Bypass model statement

In research that Southgate (2004) has done he explained that in more than a hundred years of pigging history the pigging process has changed very little, with the exception being the development of intelligent pigs for inspection. Different rule of thumb was developed during the years due to the fact that pigging is a blind operation as mentioned in section 2.4. These rules of thumb dictate pig design, pig speed and cleaning frequency. A lot of caution is put in the process as over aggressive cleaning can remove more than preferred deposit and plug the line, causing the pig to get stuck inside of the pipeline. Where there is a large build-up of wax expected a common approach would be to pig the line using progressively harder foam pigs until the operator has sufficient confidence to introduce a full-bore metal-bodied pig. Below are some of the pig that is currently used in the industry and their applications.

Sphere and foam pigs:

Sphere and foam pigs are used for the same application as standard pigs, however they are able to negotiate some piping configurations that standard pigs cant and could be magazine loaded so that the system could be mechanically automated (Figure 17).

Figure 17: Sphere and foam type pigs

2 cup pigs:

2 Cup pigs are generally used for batching of dissimilar fluids and in the case where 1.5D bends were used in the process pipeline (Figure 18).

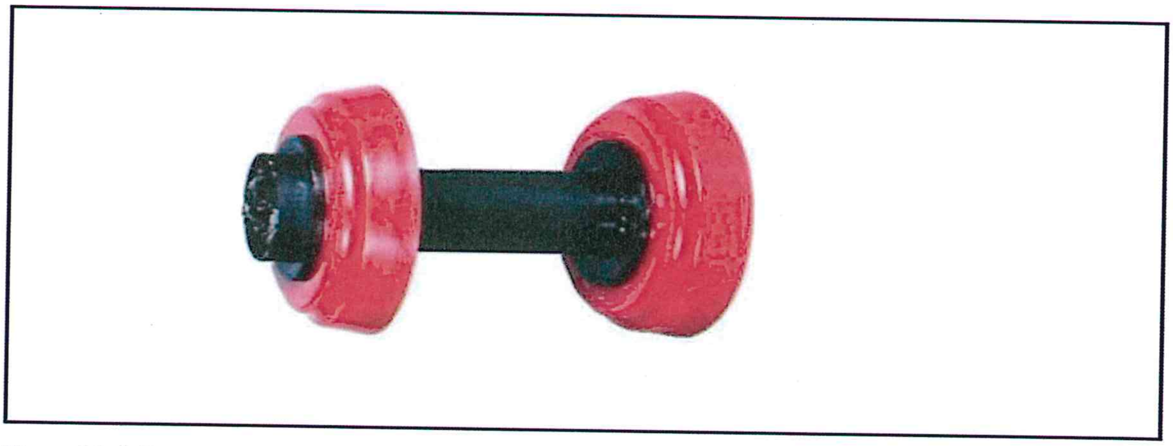

Figure 18: 2 Cup type pigs

4 cup pigs:

4 Cup pigs provides a positive seal dissimilar fluid and are typically used in case where there are two different fluids going to the same destination over a long distance but should be kept separate from each other (Figure 19).

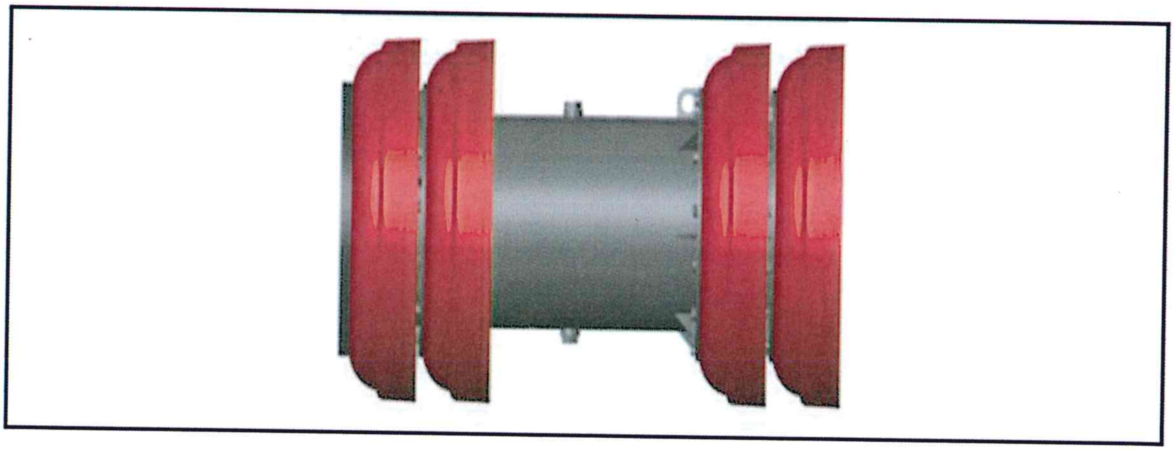

Figure 19: 4 Cup type pigs

Disc pigs:

Disc type pigs are used for standard pigging operations such as dewatering during hydrostatic testing, routine batching operations, and certain types of product removal even when bidirectional operations are required. These types of pig are more effective with product separation than the 4 cup type pigs (Figure 20).

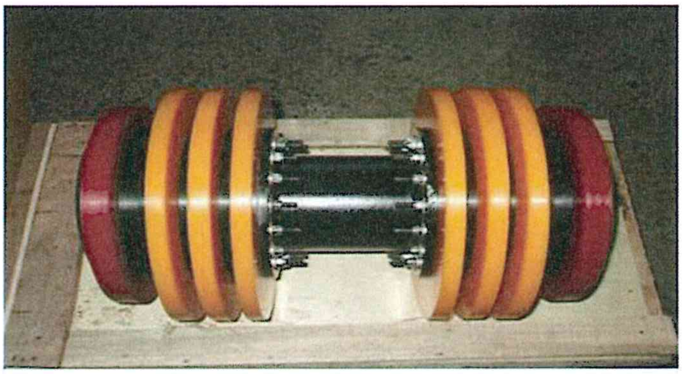

Figure 20: Disc type pigs

Cup brush type pigs:

Cup brush type pigs are primarily used for product removal, batching, hydrostatic testing, and paraffin, debris or other buildup removal. They are also much lighter in weight than steel-mandrel pigs which allows for longer and more efficient runs (Figure 21).

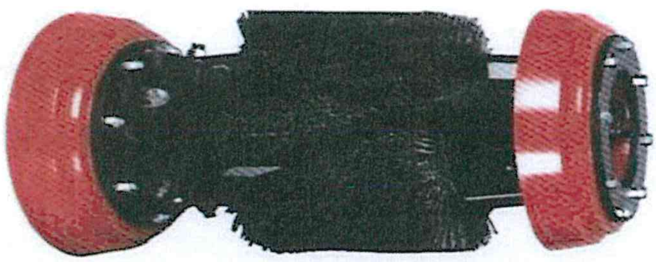

Figure 21: Cup brush type pigs

Disc brush type pigs:

Disc brush type pigs are primarily used for product removal, batching, hydrostatic testing, and paraffin, debris or other buildup removal. Disc type pigs have a better sealing capability than the cup brush type pigs which will make them the preferred type of pig to use between two dissimilar fluids (Figure 22).

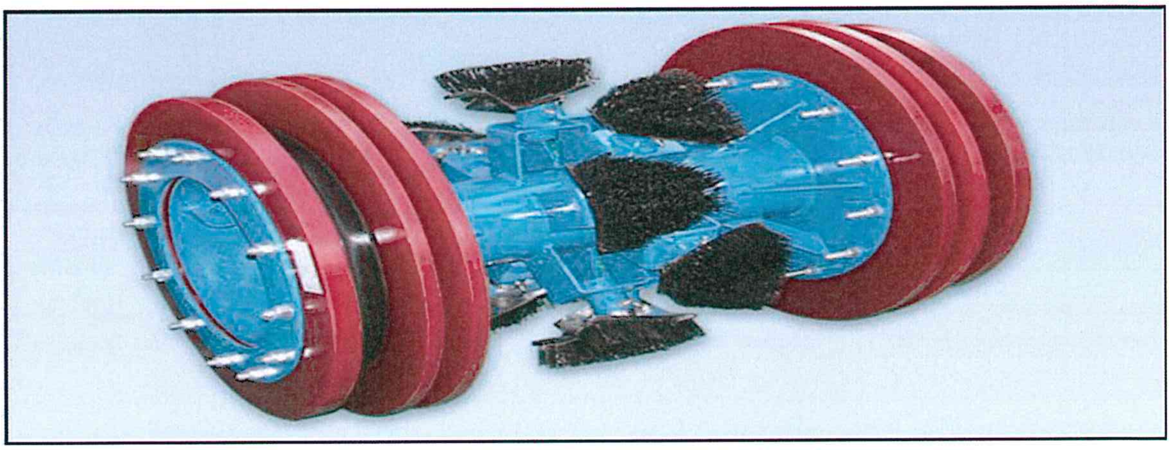

Figure 22: Disc brush type pigs

4 Cup bypass pig

The design of a bypass pig are designed for optimal cleaning at around 5 m/s In large pipelines where there is very high velocities, operators are reluctant to reduce the flow down for pigging, as this normally result in a reduction of revenue. Pigtek (2010) have specifically designed bypass pigs for these cases where the operators are reluctant to reduce the velocity for pigging. These particular bypass pigs can react to changes in speed and automatically slow down or speed up. Adding additional bypass holes or increasing the bypass area can be useful for moving loose deposits ahead of the pig.

Figure 23:4 cup bypass pig (www.pigtek.com)

By introducing a bypass model the risk of plug formation can be reduced immensely as shown in figure 24. This is usually achieved by using a hollow mandrel or by placing holes in the pig seals or discs. The bypass model not only slows down the pig but also promotes a turbulent jet in front of the pig to allow the removed deposits to be transported away in the bulk flow of the oil. Hence the reason why the bypass model became the preferred method to use when pigging a subsea pipeline.

To date there is a lot of work being done to prove how effective bypass flow is in deterring plug formation. For this reason, sizing and placement of bypass holes is largely intuitive on the part of manufacturers which will then be taken into consideration when doing the calculations for the specific pipeline.

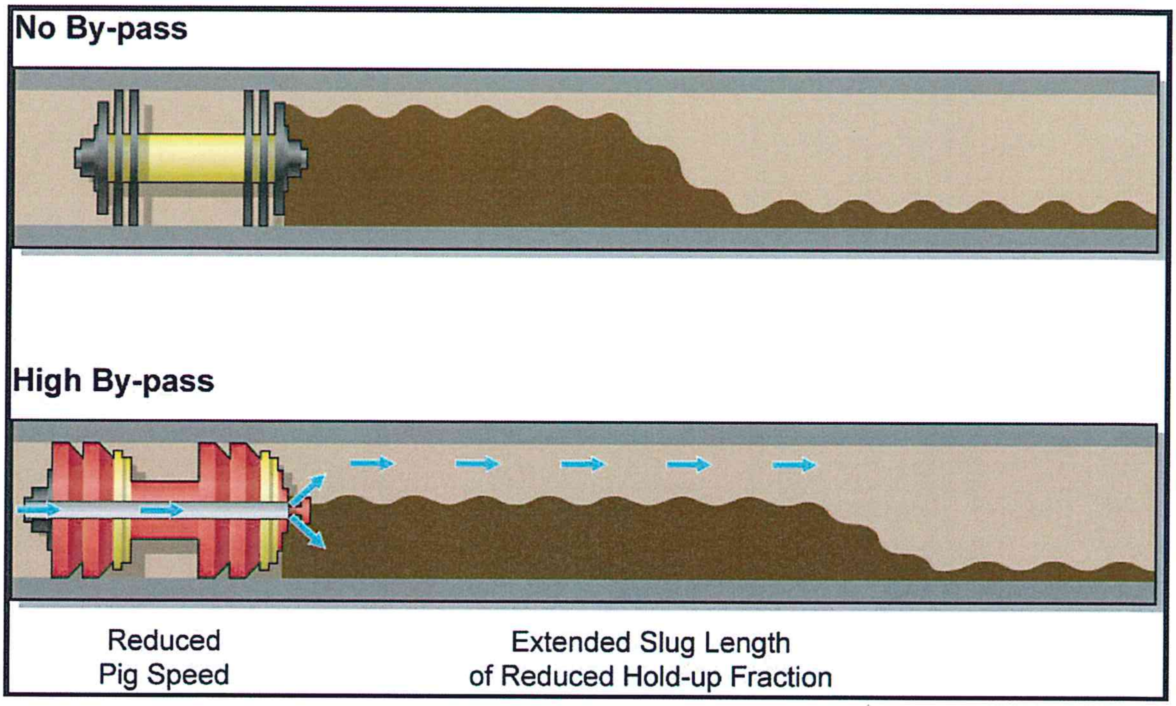

Figure 24: High bypass pig vs no bypass pig (www.emby.us)

3.2.2 Bypass model equation

As described in the previous section 3.2.1, bypass flow through the pig was introduced to prevent build up of waxes downstream of the pig. The dislodge waxes in front of the pig tends to get compressed and forms a solid plug. The plug causes an increase in frictional forces between the plug and the pipe wall. Bypass allows the oil from the reservoir to flow through the mandrel or through the holes in the scraping discs. The volumetric flow through the orifice of the pig can be found by an expression derived from Bernoulli's equation. See below for derivation of bypass flow equation.

Bernoulli's equation reduces to an equation relating the conservation of energy between two points on the same streamline:

$$P_1 + \frac{1}{2}\rho V_2 = P_2 + \frac{1}{2}\rho V_2^{\,2}$$

Re-write:

$$P_1 - P_2 = \frac{1}{2}\rho V_2^{\,2} - \frac{1}{2}\rho V_1^{\,2} \quad \text{.......(3.2.2.1)}$$

Continuity equation:

$$Q = A_1V_1 = A_2V_2$$

$$V_1 = \frac{Q}{A_1} \text{ and } V_2 = \frac{Q}{A_2} \quad \ldots\ldots(3.2.2.2)$$

Adding Bernoulli´s (3.2.1) into equation (3.2.2):

$$P_1 - P_2 = \frac{1}{2}\rho\left(\frac{Q}{A_2}\right)^2 - \frac{1}{2}\rho\left(\frac{Q}{A_1}\right)^2 \quad \ldots\ldots(3.2.2.3)$$

This can be solved for Q the pigging frequency:

$$Q = A_2\sqrt{\frac{2(P_1 - P_2)/\rho}{1-\left(\frac{A_2}{A_1}\right)^2}}$$

And can be re-written as:

$$Q = A_2\sqrt{\frac{1}{1-\left(\frac{d_2}{d_1}\right)^4}}\sqrt{\frac{2(P_1 - P_2)}{\rho}} \quad \ldots\ldots(3.2.2.4)$$

Beta factor is the facto required between the orifice hole of the pig and the diameter of the pipe:

$$\beta = \frac{d_2}{d_1} \quad \ldots\ldots(3.2.2.5)$$

Where:

Q	volumetric flow rate (at any cross-section), m^3/s
A_1	cross-sectional area of the pipe, m^2
A_2	cross-sectional area of the orifice hole, m^2
d_1	diameter of the pipe, m
d_2	diameter of the orifice hole, m
β	ratio of orifice hole diameter to pipe diameter, dimensionless
V_1	upstream fluid velocity, m/s
V_2	fluid velocity through the orifice hole, m/s
P_1	fluid upstream pressure, Pa with dimensions of $kg/(m\cdot s^2)$

P_2	fluid downstream pressure, Pa with dimensions of kg/(m·s^2)
ρ	fluid density, kg/m^3

Adding coefficient of discharge to the equation will result in the following:

$$Q = C_d A_2 \sqrt{\frac{1}{1-\beta^4}} \sqrt{\frac{2(P_1 - P_2)}{\rho}}$$

Meter coefficient to obtain the final equation for the volumetric flow of the fluid:

$$C = \frac{C_d}{\sqrt{1-\beta^4}} \quad \text{.........(3.2.2.6)}$$

Adding the meter coefficient to the equation leads to the bypass flow equation:

$$Q_{bypass} = A_{bypass} C_d \sqrt{\frac{2\Delta P}{\rho}}$$

Bypass flow:

$$Q_{bypass} = C_d \sqrt{\frac{2\Delta P}{\rho}} A_{bypass} \quad \text{.........(3.2.2.7)}$$

Where:

C_d	Discharge Coefficient (Typically 0.7);
ΔP	Differential Pressure across pig;
ρ	Oil density;
A_{bypass}	Bypass area;
Q_{bypass}	Volume flow through bypass;

O´Donoghue (2004) proposed an estimated pig frequency of bypass size for a de-waxing pig. The principle states that the bypass flow rate should be greater than the rate of incoming wax, see Equation 3.2.2.8. If this is criteria is met, there will be a small amount or no wax accumulation in front of the pig and wax simply gets flushed away (O'Donoghue, 2004). If the bypass rate is not adequate the wax may start to accumulate and form a plug. The volume flow of wax that needs to be flushed away can be estimated using Equation 3.2.2.9. Note that the efficiency of wax removal efficiency for the pig affects the total wax amount.

$$Q_{bypass} > Q_{wax} \quad \text{.........(3.2.2.8)}$$

$$Q_{wax} = v_{pig} A_{wax} \eta \quad \text{.........(3.2.2.9)}$$

The bypass system will allow the operator to adjust the pig velocity to the desired velocity required for the process. By simply changing the bypass area of the pig, will let more flow through the pig that slows down the pig velocity and can be calculated using Equation 3.2.2.10. Equation 3.2.2.8 will be rearranged and used to determine the pig velocity as well as the number of days to launch a pig. From Southgate (2004) substituting equation 3.2.2,7 into equation 3.2.2.9 the following equation 3.2.2.10 will be derived for pig velocity:

$$v_{pig} = \frac{v_{oil} A_{pipe} - C_d \sqrt{\frac{2\Delta P}{\rho}} A_{bypass}}{A_{pipe}} \quad \text{.........(3.2.2.10)}$$

(J.M. Sullivan, 1981) The average pigs normally consists of two or more polyurethane rings fixed to a cylindrical steel hub, even though there are different types of cylindrical pigs such as pigs made of foam rubber that are also used. The pigs outer diameter is usually a bit bigger larger than the inner pipe diameter. This causes the pig to have a tight seal which then creates a differential pressure across the pig; this pressure then pushes the pig through the pipe. Below is the equation on how one would go about calculating the deferential pressure of a pig.(D. Wint, 2007) Typical Differential Pressure (DP) required forcing a pig through a pipeline:

$$DP(bars) = \frac{K(type\ of\ pig)}{No\min al\ Diameter\ (inches)} \quad \text{.........(3.2.2.11)}$$

K (Types of Pigs):

- Sphere and Foam Pig = 1
- 2 Cup Pig = 4
- 4 Cup Pig = 7
- Disc Pig = 9
- Cup Brush Pig = 12
- Disc Brush Pig = 15
- UT ILI Tool = 19
- MFL ILI Tool = 24

A coefficient of discharge C_d was introduced to the equation to compensate for fictional losses, velocity and turbulence effects. The coefficient of discharge C_d is a dimensionless number. The most common value used for the coefficient of discharge is 0.7. The bypass area varies from pig to pig, depending on the field of operation and its requirements. In a paper by O'Donoghue (2004) it is used bypass ports that can vary the opening from 0.25 % by area and up to 2 % for his calculations (O'Donoghue, 2004). In a paper by Lee, et al, (2012) a bypass-area of 0 to 13 % has been used.

Now that the pig's velocity and differential pressure equations have been determined the next step will be to determine the rate at which the wax approaches the pig. From O'Donoghue (2004) the equation for rate at which wax approaches the pig are as follows:

$$Q_{wax} = N\, v_{pig} \pi\, d\, t_{wax,daily} \quad \text{..........(3.2.2.12)}$$

Rearranging Equation 3.2.2.12 and substituting it into Equation 3.2.2.8 the pigging frequency in days, N, (or number of days between pig launches) based on this continuity criteria (Equation 3.2.2.13):

$$N < \frac{C_d \sqrt{\frac{2\Delta P}{\rho}} A_{bypass}}{v_{pig}\, \pi\, d\, t_{wax,daily}} \quad \text{..........(3.2.2.13)}$$

Where:

N	Number of days between pig runs;
C_d	Discharge Coefficient (Typically 0.7);
ΔP	Pig Differential Pressure;
ρ	Oil density;
A_{bypass}	Bypass area;
V_{pig}	Pig Velocity;
d	Pipeline Internal Diameter;
$t_{wax,daily}$	Maximum daily wax deposit

When taking any subsea pipeline one can work out their pigging frequency for that particular case using the above equations and a basic graph can be drawn to show their ultimate pigging frequency as shown in figure 25. This figure shows the operator what is the exact pigging frequency required to launch a pig to get the maximum flow assurance. In more detail the friction forces can also be calculated to give the operator an even more accurate frequency.

This calculated frequency can be adjusted to suit the specific requirements of the pipeline and crude oil by simply increasing the bypass area of the pig or to increase or decrease the velocity that the pig travels through the pipeline which will increase or decrease the duration that it takes the pig to travel through the pipe. It will also mean that one can shorten or lengthen the number of days required to launch a pig. These are all specific variables that can vary for each individual case. The difficult part is to determine the productions needs and to establish what the consequences will be when not operating in those regions.

Therefore an explanation of what could be the consequences in not operating at the optimized frequency Point A but instead operating in different regions B, C, D, E as shown in figure 25.

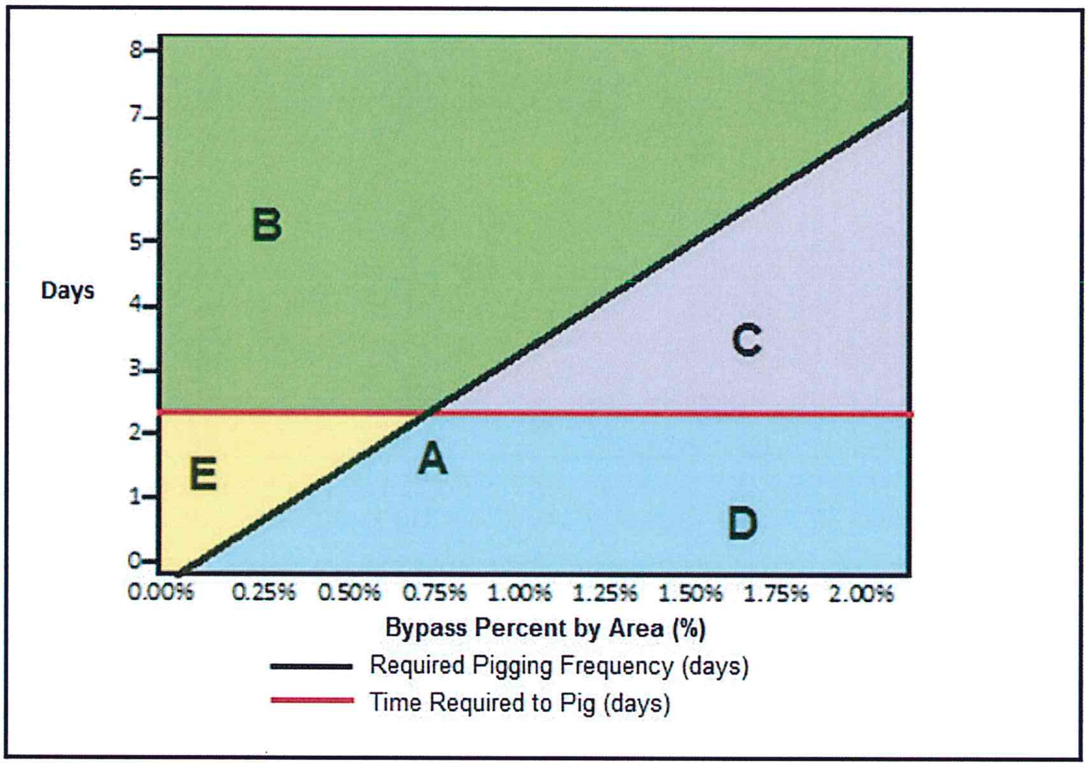

Figure 25: Calculated pigging frequency.

Point A

This point is the point where the most optimized pigging frequency is calculated using the equations given in section 3.2.2. At that exact point it shows the desired pigging frequency with a specific bypass area and the duration it will take the pig and complete one full cycle. It also shows that the moment the pig gets caught at the receiving station the next pig gets launched at the launching station. This means that essentially there will be at least one pig in the pipeline at all times which will cleaning of the pipeline at all times.

Region B:

This region is where the pig gets launched later than the calculated pigging frequency. In this region the pigs velocity will slow down tremendously due to opposing forces such as friction forces, wax reaction forces etc. This is the most dangerous region to launch a pig because of the likelihood of excess buildup of waxes in front of the pig. The thickness of the precipitated waxes against the pipe wall will be more than the $t_{wax,daily}$ used in the calculation to calculate the pigging frequency. The reaction forces will most likely be grater that the driving forces of the pig. This will be the region in which it is highly likely for the wax to form a plug in front of the pig and the pig will get stuck inside the pipeline that will lead to a blocked pipeline.

Region C:

This region is where the pig gets launched earlier than the calculated pigging frequency. In this region the pig gets launched to early. This will be the same as for region B in the sense that the pipe line doesn't get launched as regular as required but due to the fact that the pig has a larger bypass area will mean that it will still be able to be pushed through the pipeline. The velocity of the pig will be affected due to the precipitated waxes against the pipe wall that is thicker that the $t_{wax,daily}$ calculated but will still be able to withstand the forces such as friction forces, wax reaction forces etc. This region will also be a dangerous region to launch a pig because if not carefully monitored the operator might move into region B and there is still a possibility of wax build up in front of the pig that could lead to a blocked pipeline.

Region D:

This region is where the pig also gets launched earlier than the calculated pigging frequency but the difference between region C and region D is the fact that the pigs bypass area is big enough to freely move through the pipeline without any estimated problem. If Point A cannot be met by the operator due to unforeseen circumstances this will be the safest region to operate in. The pig gets launched more frequent than required and will most like never see the maximum $t_{wax,daily}$

that was used to calculate the pigging frequency. The only problem with this is launching more pigs than required could potentially cost the oil production company more money unnecessarily.

Section E:

This region is tricky because the pig gets launched later than the calculated pigging frequency but the duration that the pig takes to complete one full cycle is much quicker. This could be due to the fact that the bypass area is larger than calculated which makes it much easier for the pig to navigate its way through the pipeline. This region is also a very safe region to operate in and could most possibly be the most cost effective solution is subsea pigging. The same costs are involve but by simply over sizing the bypass area will give the operator the freedom launch the pig later than was calculated and also manage to pig the line much faster that calculated.

4 CHAPTER 4: RESULTS AND ANALYSIS

In this chapter one case study will be taken its pigging frequency will be calculated and discussed to show the optimized pigging frequency for the particular case.

This case study is based on a 36" deep-water pipeline, 274 km long and 115 m deep see Figure 26]. The oil flows at a rate of 0.46 m/s (650 000 bbl/day) (Lundin-Petroleum, 2012).

(Lundin Norway, 2013) Assuming that there is a rapid heat loss down in the pipeline because of the depth and distance of the pipeline underneath the sea water, this allows the temperature of the oil to cool down to its wax appearance temperature and wax is to stat to deposit against the pipe wall. There is assumed that the maximum wax build up will be 2.5mm per day. The output curves are shown in [Figure 27].

(J. Wellinghoff, 2009) the maximum operating pressure in the pipeline is 92 MPa.
All these variables could just be tweaked ones all the unknown variables has been confirmed.

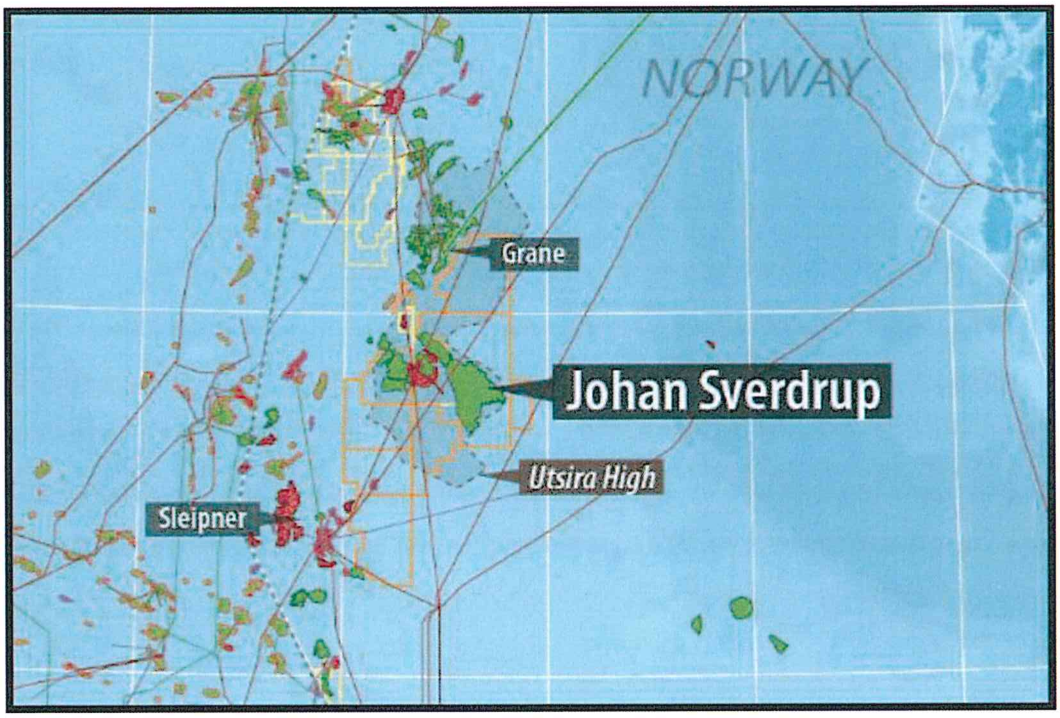

Figure 26: Wax Deposition Curve

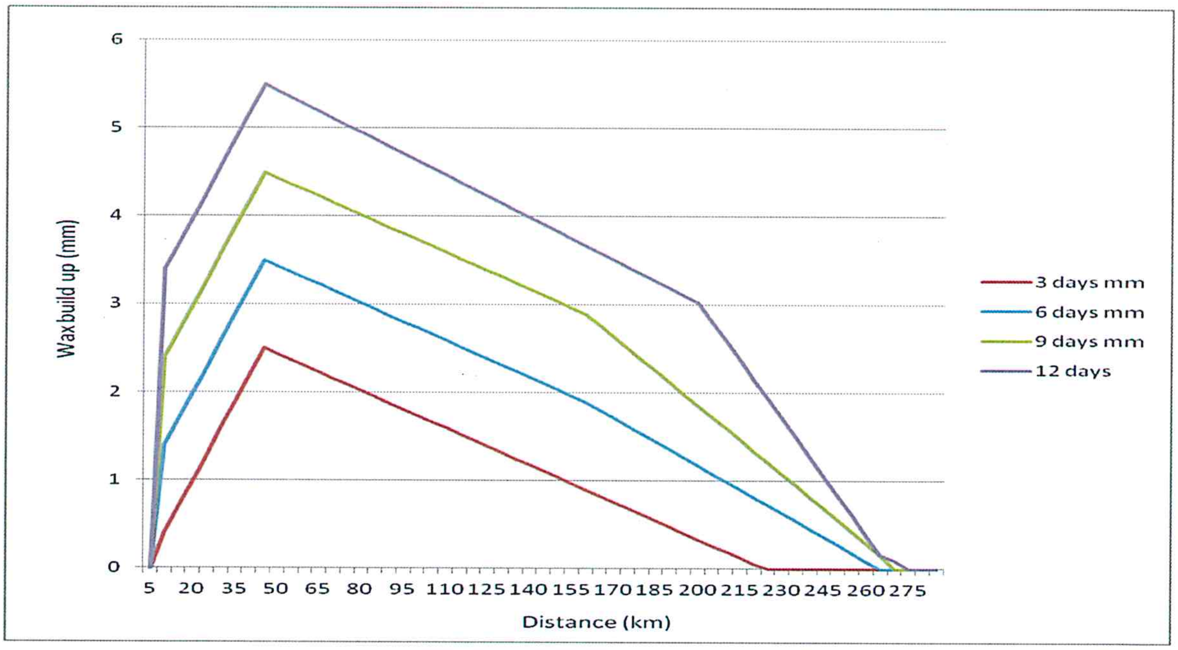

Figure 27: Wax Deposition Curve

Using equation 3.2.2.10, 3.2.2.11 and 3.2.2.13 to plot the graph figure 29 to calculate the optimum pigging frequency.

$$DP(bars) = \frac{K(type\ of\ pig)}{No\min al\ Diameter\ (inches)}$$

Where:

K (disc type pig)	= 15
Nominal diameter	= 36in (882 mm)

Equation 3.3.3.11 to calculate the velocity of the pig.

$$v_{pig} = \frac{v_{oil} A_{pipe} - C_d \sqrt{\frac{2\Delta P}{\rho}} A_{bypass}}{A_{pipe}}$$

Where:

V_{oil}	= 0.46 m/s
A_{pipe}	= 0.576 m^2
C_d	= 0.7
ΔP	= 0.417
A_{bypass}	= 0% to 8%

And using equation 3.2.2.13 to calculate the optimum frequency.

$$N < \frac{C_d \sqrt{\frac{2\Delta P}{\rho}} A_{bypass}}{v_{pig}\ \pi\ d\ t_{wax,daily}}$$

Where:

V_{pig}	= 0.405 m/s to o.46 m/s
A_{pipe}	= 0.576 m^2
C_d	= 0.7
ΔP	= 0.417
A_{bypass}	= 0% to 8%
d (internal diameter)	= 856.6 mm
$t_{wax,daily}$	= 2.5 mm per day

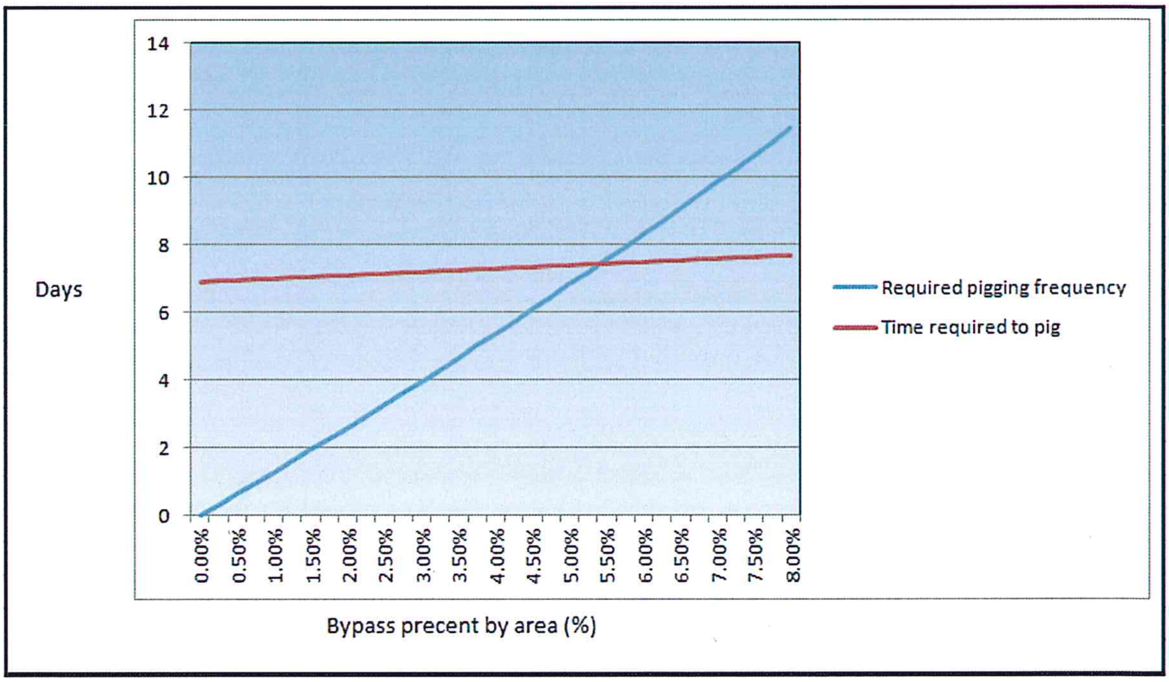

Figure 28: Calculated pigging frequency

The calculation is very conservative based on the fact that 2.5 mm of wax will only be deposited over a small percentage of the 274 km of pipe. The reason for being so conservative is because possible blockage of the bypass area or plug could have formed in front of the pig which will affect the pigs efficiency.

In this particular case the pigs velocity is varies between 0.405 m/s and 0.46 m/s which means theoretically it will take the pig between 6.9days and 7.7 days to complete one full cycle depending on the bypass area selected. This is a very long and deep pipe so it is preferred to have other precautionary systems in place which will allow the production team to track and locate the pig to make sure that nothing goes wrong and the pig doesn't get stuck along the way. Another precautionary measure that can be taken is to launch more than one pig at a time and more frequent or to increase the bypass area so that the operator operates between region D or E just to ensure that the line does not allow for maximum build up of wax in the pipeline. The region to operate in should be evaluated by the production company to see what would be the most feasible option.

The pig used for this case study would be a standard bi-directional disc brush pig with bypass ports to allow for between 0% and 8% as shown in figure 28. The different bypass sizes allow the production company to make a choice between different options to find the best suitable pigging frequency to suit their needs. Additional discs, brushes and spacer can also be added to the pig for even better sealing capabilities which results in better cleaning of the pipeline and also better efficiency.

All these variables could be adjusted to find their optimum frequency.

5 CHAPTER 5: CONCLUSION

- Pigging of the pipeline must happen at a given frequency to prevent the wax from going past its maximum wax thickness.
- A Model has been presented for a bypass pig cleaning in operation. Assumptions have been done to calculate the number of days. Results in this thesis shows that the number of days required for pigging could be adjusted to suit the production company needs by simply launching a pig more frequent than required or to increase the bypass area. It still stays difficult to find realistic number without experimental data for some of the variables for the real pipeline system.
- Pressure drop calculations for a pipeline with wax deposition have been done. Results show that the using different pigs have different differential pressure. A pigging operation reduces the pressure drop in the pipeline if the pig efficiency is high or the pig has efficient bypass flow.
- Calculations were done on one case study. The objective for this research was to optimize the frequency to launch a pig. Part of this was to involve the bypass pressure; bypass area, density of the oil, velocity of the pig and the thickness of wax deposition against the inside wall of the pipe. All these variables have an impact on the frequency. Results shown that even with an optimized pigging frequency one can still be flexible by simply increasing the bypass are or pigging more frequent than calculated. The main objective is for the production companies to determine their own needs and compare costs to get the maximum revenue.
- It may be concluded that the calculations that was done on the case study was sufficient and theoretically would be able to keep the pipeline clean and free of any wax build up to ensure maximum production without any downtime. These variables could be adjusted ones more detailed information is available for these particular cases.
- It was also proved to be the cheapest option available to ensure that the pipeline stays clean. It does have a reasonably high input cost when considering the cost of the pig and pipe fittings required to manufacture the pig launcher and receiver etc, but it is considerably cheaper that cleaning a blocked pipe.

6 CHAPTER 6: RECCOMENDATION

More knowledge about how the wax adheres to the pipe wall is of interest when finding the maximum wax build up in n pipeline. The equations should be tested against real experiments to check the credibility of the expression.

In this study it was proven that it is possible to keep an oil production pipeline clean from wax with pigging and that is very cost effective. It was also found that it is one of the most cost effective ways to keep a pipeline clean and to ensure optimal production.

This is based on theory only and some of the variables could change in time due to better knowledge of the pipelines and its conditions gathered during operation. It is recommended that the following variables are checked and verified before pigging frequency can be finalized:

- Thickness of wax build up on the inside wall of the pipe.
- Lengths of wax build up in the pipeline.
- Pig that will be used for each case study.
- Bypass area of the pig
- Pigs velocity.
- Pressure drop across the line.
- Density of the oil.

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7 APPENDIX A: WORLD PETROLEUM PRODUCT DEMAND

	2008	2009	2010	2011	2012	% change 12/11
Algeria	516.5	411.6	631.5	501.3	451.5	-9.9
Gasoline	60.9	60.9	69.5	51.3	50.8	-1.1
Kerosene	21.6	57.2	34.1	24.3	24.3	-
Distillates	178.0	166.5	180.7	154.3	126.4	-18.1
Residuals	121.6	92.6	118.7	117.0	86.7	-25.9
Others	134.5	34.3	228.5	154.4	163.3	5.8
Angola	47.8	46.2	47.0	39.4	38.7	-1.8
Gasoline	1.8	0.9	1.3	1.3	1.5	15.2
Kerosene	7.0	10.0	8.5	7.0	7.8	10.8
Distillates	10.8	10.4	10.6	10.6	10.8	1.5
Residuals	11.0	13.7	12.4	16.4	16.3	-0.5
Others	17.2	11.2	14.2	4.1	2.4	-42.1
Ecuador	194.3	189.3	185.1	217.3	132.9	-38.9
Gasoline	44.7	46.1	41.4	55.3	28.3	-48.7
Kerosene	8.5	8.2	8.1	8.3	8.2	-0.7
Distillates	32.9	35.6	32.8	37.9	42.1	11.0
Residuals	65.0	66.9	60.1	67.8	32.6	-51.9
Others	43.2	32.5	42.7	48.0	21.6	-55.0
IR Iran	1,587.0	1,726.1	1,743.3	1,770.2	1,774.8	0.3
Gasoline	306.3	332.6	346.3	330.0	344.4	4.4
Kerosene	159.5	119.2	130.2	116.9	124.5	6.5
Distillates	503.1	556.3	565.5	598.1	1,068.9	78.7
Residuals	462.2	494.4	472.0	487.2	99.5	-79.6
Others	155.9	223.7	229.3	238.0	137.4	-42.3
Iraq	453.2	456.6	513.2	613.2	580.4	-5.3
Gasoline	59.9	60.1	71.8	75.4	76.4	1.2
Kerosene	46.7	47.8	51.5	87.4	44.5	-49.1
Distillates	83.7	85.5	102.2	130.1	127.6	-1.9
Residuals	209.5	210.9	246.5	217.2	282.4	30.1
Others	53.3	52.2	41.2	103.2	36.3	-52.0
Kuwait	1,003.2	892.7	979.4	881.9	1,057.0	19.9
Gasoline	54.2	55.7	54.9	56.9	52.4	-7.9
Kerosene	171.8	182.6	182.6	176.9	180.8	2.2
Distillates	243.3	300.6	243.5	244.8	227.6	-7.0
Residuals	184.8	144.4	204.8	180.2	199.8	10.9
Others	349.1	209.4	293.7	223.1	396.4	77.7

	2008	2009	2010	2011	2012	% change 12/11
Libya	352.6	350.0	368.3	341.3	149.2	–56.3
Gasoline	18.2	17.6	16.2	17.7	15.1	–15.1
Kerosene	34.3	41.9	43.3	47.5	16.2	–65.9
Distillates	84.4	89.4	96.4	78.8	46.2	–41.3
Residuals	141.2	131.3	141.1	137.0	41.4	–69.8
Others	74.5	69.9	71.3	60.3	30.3	–49.7
Nigeria	80.0	41.4	87.7	100.3	82.4	–17.8
Gasoline	12.0	10.5	23.9	29.7	27.4	–7.7
Kerosene	43.4	7.0	13.7	16.0	12.9	–19.3
Distillates	21.3	22.9	20.6	46.9	37.2	–20.7
Residuals	0.4	0.2	24.1	4.0	2.3	–44.3
Others	2.9	0.9	5.3	3.6	2.6	–28.9
Qatar	126.2	126.3	133.0	127.0	122.7	–3.4
Gasoline	44.6	40.7	44.5	43.5	42.3	–2.8
Kerosene	24.2	22.8	24.6	23.3	23.3	–
Distillates	24.3	31.8	27.5	27.4	31.9	16.6
Residuals	3.9	4.2	4.8	3.7	3.8	1.8
Others	29.3	26.8	31.6	29.0	21.4	–26.2
Saudi Arabia	1,970.9	1,911.0	1,914.0	1,856.7	1,927.1	3.8
Gasoline	338.8	355.1	375.6	390.6	398.6	2.0
Kerosene	190.4	174.0	168.2	166.4	174.3	4.8
Distillates	676.1	623.8	633.5	628.5	639.7	1.8
Residuals	476.5	497.6	445.4	416.9	508.4	21.9
Others	289.2	260.5	291.3	254.3	206.1	–18.9
United Arab Emirates	395.9	314.9	355.4	446.2	454.3	1.8
Gasoline	50.6	35.6	43.1	57.3	65.3	14.0
Kerosene	106.4	97.0	101.7	134.8	147.8	9.7
Distillates	86.0	73.1	79.5	99.8	85.8	–14.1
Residuals	16.5	15.3	15.9	18.3	15.8	–14.1
Others	136.5	93.9	115.2	136.0	139.7	2.7
Venezuela	1,142.7	1,232.4	1,089.1	1,472.0	1,568.7	6.6
Gasoline	309.3	307.5	306.1	441.0	427.0	–3.2
Kerosene	78.7	79.2	72.4	101.6	96.2	–5.3
Distillates	316.5	339.2	326.7	342.5	328.2	–4.2
Residuals	286.4	308.8	256.3	431.4	428.4	–0.7
Others	151.9	197.7	127.6	155.5	288.9	85.8