A NEW SMART PROCESS
FOR
PIPELINE INTEGRITY MONITORING

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DECLARATION

I can confirm that no material described in this thesis has been submitted for the award of any other degree or qualification in any other university or college of advanced education.

I can also confirm that any concept or diagram not explicitly acknowledged in this thesis is an original personal work or are derived as part of a non-confidential work for which I was a team member.

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11 May 2021

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ABSTRACT

Most of the prospecting areas used for hydrocarbon exploitation in the Niger Delta were originally virgin lands but has suffered urban encroachment such that any hydrocarbon loss of containment would lead to pollution, loss of lives, major fires, and loss of major assets. Pipeline loss of containment during petroleum evacuation were mainly due to corrosion but around the year 2000, pipeline vandalism which started as a way of protesting lack of development projects by host communities, rapidly grew into an industry for crude theft through hot tapping. The cost of crude oil theft is estimated at £1bln per month and it is reported that some 1000 people have died due to pipeline explosion in Nigeria within the period 2004 to 2014.

Several unsuccessful initiatives like amnesty and employment of repentant oil thieves by government; burying originally surface pipelines, and regular helicopter surveillance overflies along pipeline routes were attempted to arrest the pipeline vandalism environment. This research is a new initiative in the fight against crude oil theft through a technical process that provide an early information to the operator of the position and rate of crude oil theft such that the situation could be appropriately arrested, thereby creating revenue security, preventing loss of containment fires, and potential deaths that could have arisen if there is explosion due to loss of containment.

Two analytical methods, which uses the pipeline pressure gradient as a basis were independently verified in leak point identification and leak rate estimation in the proposed smart process for pipeline integrity monitoring. The leak point identification is based on pressure gradient relaxation while the leak rate estimation is based on enclosed angle vector relaxation. A near perfect (100%) accuracy in leak point determination and a 93.44% average leak rate prediction accuracy was demonstrated based on the proposed smart process for pipeline integrity monitoring.

Some of the advantages of this new process is simplicity, retrofit ability and no demand for skills reassessment for operators as it fits into normal operations. The enclosed angle vector relaxation concept, which is one of the main contributions of this research: is a new knowledge addition to Physis and Fluid Mechanics; a discovery and a process invention.

List of Abbreviations and Acronyms

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1 INTRODUCTION

1.1 Introduction

The demand for petroleum and natural gas, which accounts for one third of total energy supply needed to support human development through the provision of vital raw materials for habitation, medication, transportation and industrialization, is projected to continue to increase with time, hence the focussed effort on process safety improvements during hydrocarbon exploration, production, processing and transport (Nwankwo, 2013). Hydrocarbon or petroleum exploitation process involves all activities towards the mining of oil and gas and their transport to the point where they are needed. The mining process and activities are executed in hazardously classified areas where strict personal and process safety measures are enforced. The transport process involves the use of pipelines to convey crude oil from wellheads to flowstations or from the flowstations to the central processing plant via major pipeline that are called trunklines. The crude oil being transported are inflammable, toxic, and are usually pumped under high pressure through sensitive environments like farmlands, forest reserves, urban developments, and seabed.

Most of the prospecting areas used for oil exploration and developments in the Niger delta, which started in the 1950s, were virgin lands for which what was considered appropriate due diligence environmental impact assessments were made and requisite approvals from the respective jurisdictions sought and received. However, because of urbanisation, some of these approved facility sites (well locations, gathering stations, and pipeline right of ways) became encroached such that any pipeline loss of containment leads to pollution, loss of lives, major fires and loss of major assets. Figure 1 shows an encroached pipeline ROW in the Niger delta (The Guardian, 2005). Most times the residents on these encroached sites do not quite appreciate the impact of any accidental loss of hydrocarbon containment and some of these encroachment situations have compelled shut-in of several facilities by the IOCs to minimise liabilities during accidents.

Figure 1. Pipeline ROW encroachment site (The Guardian 2005)

Accidents occur when risks are not accurately assessed or mitigated. A single accident could have huge effect on operating cost and safety. The lost time injury frequency (LTIF) rate, which is a quantification of lost time injuries occurring in a workplace per million hours worked, has been devised within EP industry and indeed universally as a critical key performance indicator (KPI) for accident prevention. This LTIFs could be considered as visible tip of an iceberg that provides a warning sign of the large mas of ice buried under water. This is because any visible manifestation of an accident must have been surrounded with several unsafe conditions and near miss incidents. Through the monitoring of LTIF, high potential incidents are reviewed and properly mitigated before they could lead to accidents. These reviews assess the incident probability of occurrence and the consequences of such occurrence. The fact that an event has a low probability of occurrence does not necessarily mean that it will not happen, hence the evaluation of the potential consequences of any major loss of containment event should be the focus of every risk assessment as the cost of accidents could be huge and capable of having a significant effect on company's bottom line: cost of impacted lives; damage to facilities; environmental remediation cost; associated litigation cost; loss of revenue etc. Usually, stringent procedures are instituted to mitigate any risk that is assessed as having a high impact irrespective of the assessed probability of occurrence.

The hydrocarbon mining activities include seismic acquisition; interpretation and mapping; drilling; hydrocarbon processing; and transportation. A considerable effort has been made over the years to improve on operational safety in every aspect of these mining operation around the Niger Delta. These operational safety improvement efforts that led to considerable reduction in LTIF could be classified in broad terms into improvements in 1) Legislation, 2) Regulation, 3) Monitoring, and 4) Reviews that accompany any major industrial accidents (Nwankwo 2013). Unfortunately, the hydrocarbon transport LTIF through the pipeline networks in the Niger Delta is continually on the increase since 2000.

The Pipeline network used for hydrocarbon transport in Nigeria could be classified as those related to upstream operations and those related to downstream operations. The upstream pipelines are mainly owned by the E&P companies and are used for evacuation of hydrocarbon to their respective crude oil terminals, inland refineries, or liquefied natural gas (LNG) plants. On the other hand, the downstream pipelines are used for either transportation of stabilised crude to inland refineries or for transportation of refined products from inland refineries to major product depots across the country. There are also some downstream pipelines for transportation of natural gas to cities and industrial hubs for local use. Figure 2 shows the pipeline map of Nigeria for the distribution of refined petroleum products as well as transporting crude oil to inland refineries in Kaduna, Warri, and Port Harcourt while figure 3 shows a large network of oil and gas evacuation pipeline for oil and gas processing and export.

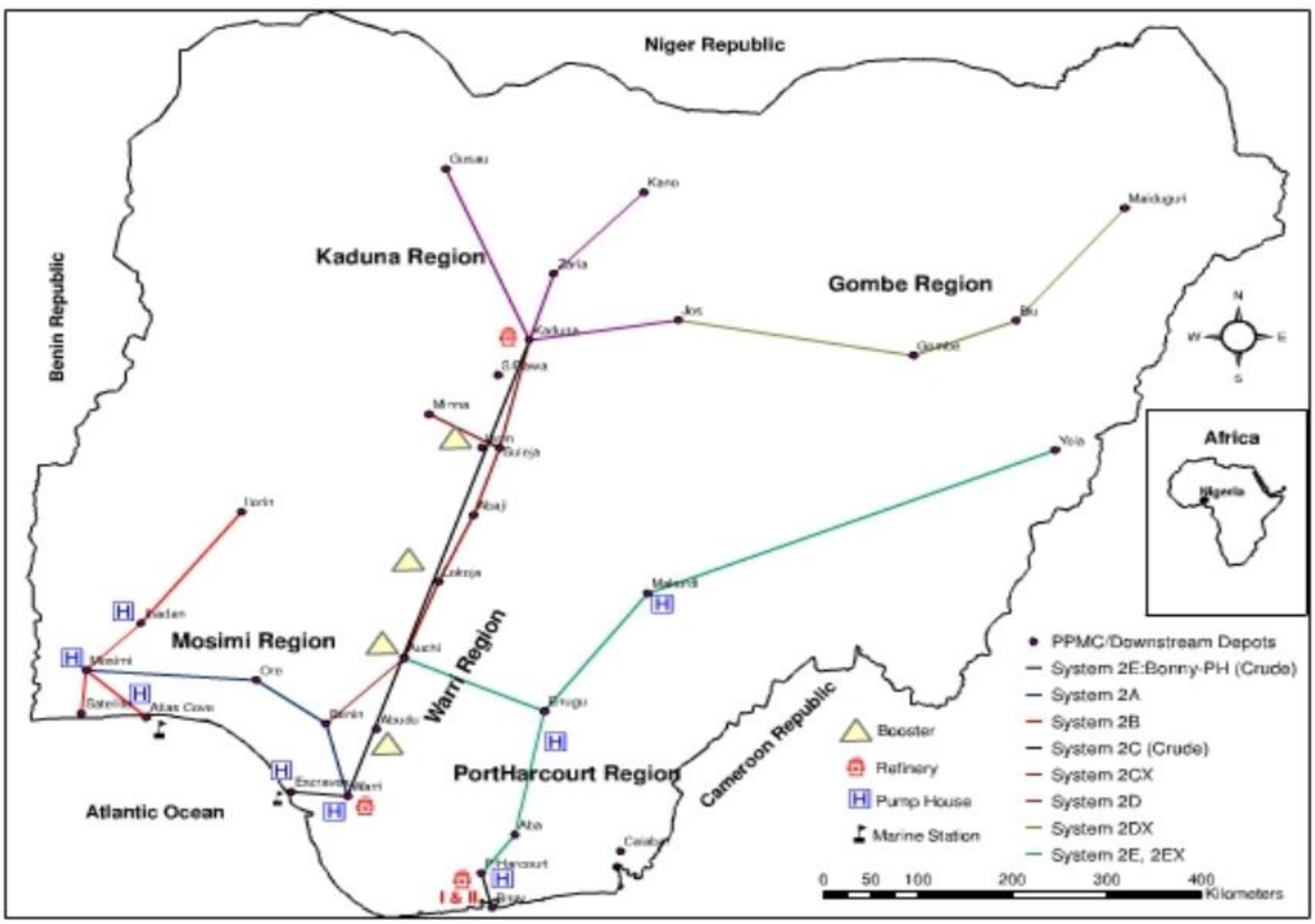

Figure 2. Downstream trunkline map of Nigeria (Aluko, 2015)

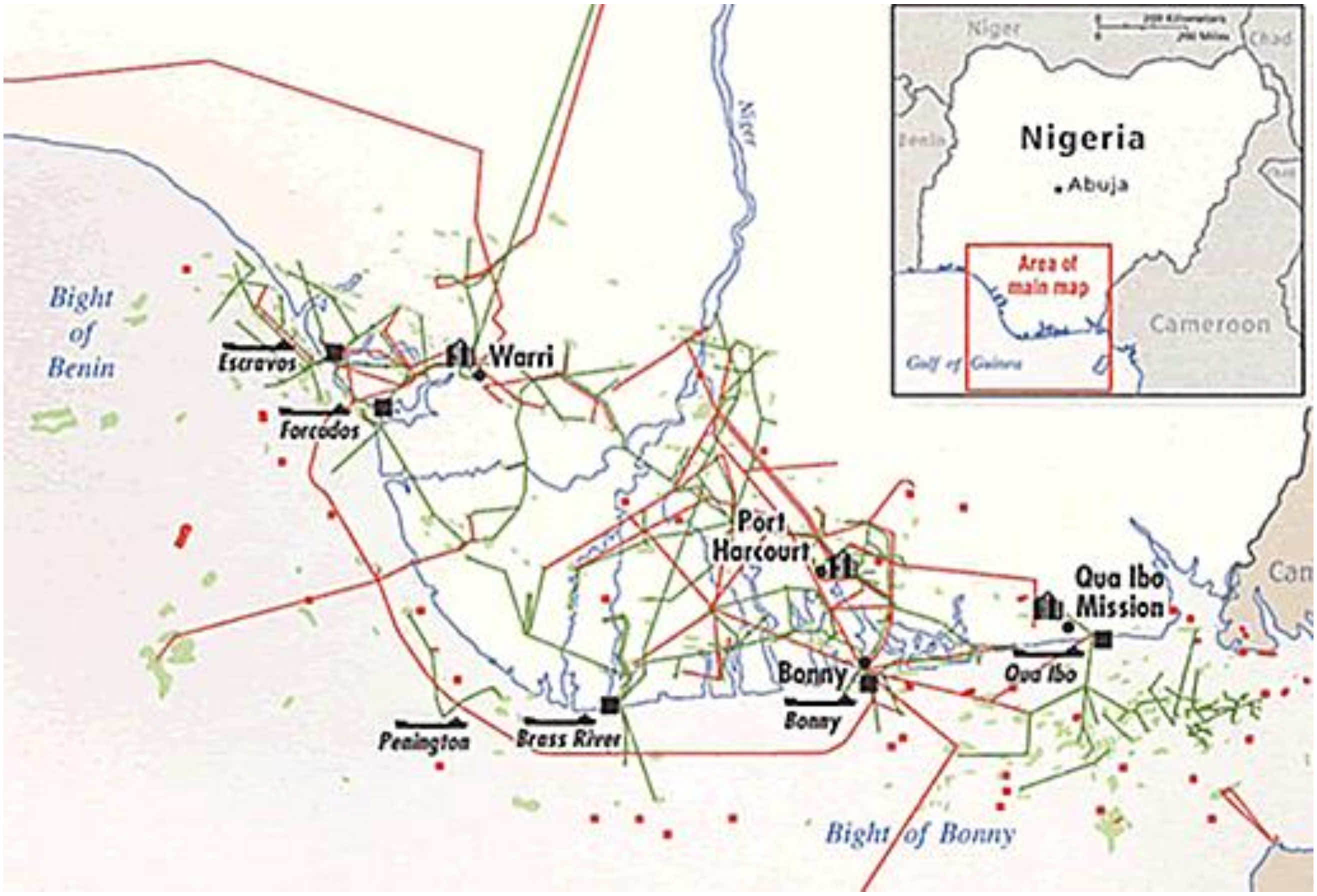

Figure 3. Niger delta upstream trunkline map of Nigeria (Analysis 2017)

These pipelines, especially the upstream pipelines, are used for continuous hydrocarbon evacuation in Nigeria and hence every effort is made to prevent any form of operational interruption on them. These crude oil and refined product pipelines have had one form of intrusion vandalism in the past and these have led to several explosions that led to tragic loss of over 1000 lives in Nigeria within the period 2004 – 2014 (Carlson et al., 2015). Stories abound where people have dug wells in their residential homes that connect to the petroleum product pipeline and from the comfort of such homes siphon and sell the products which are mainly kerosene and Prime Motor Spirit (PMS) to unsuspecting buyers (Omodanisi et al., 2014). The downstream petroleum pipeline distribution network is not always on continuous use and hence, through suspected insider information, the petroleum product vandals have knowledge of when the products are being pumped and hence use the offline periods to attach non-conventional hoses for illegal product siphoning (Anifowose et al., 2012).

The pipeline loss of containment, until late 1990s, were associated with loss of integrity hence some huge emphasis on preventive maintenance (PM) inspection and testing programmes to assess the state of such pipelines. The activities of upstream pipeline vandals started initially as a way of protesting the lack of development projects in the Niger delta host communities but rapidly grew into a major industry for crude oil theft through hot tapping. The petroleum (upstream and downstream) pipelines traverse settlements and sensitive areas hence any accidental loss of containment is always devastating, leading to multiple fatalities, suffocation or burns in addition to major environmental pollution.

Pipeline reliability improvement planning based on preventive maintenance (PM) and corrective maintenance (CM) processes worked well in the Oil & Gas industries and is still particularly useful. However, a new dimension in pipeline integrity management process was created in the Niger delta around the year 2000 when pipeline vandalism became a new issue for consideration in process loss of containment design and operation. The activities of pipeline vandals started initially as a way of protesting the lack of development projects in the Niger Delta host communities but rapidly grew into a major industry for crude theft through hot tapping.

Hot or pressure tapping is the method of attaching new conduits to an existing pipe network or pressure vessels without production interruption or depressurisation. This process is commonly used by oil companies for bringing new fields onstream, especially when there is no nearby production manifold. Figure 4, which encloses figures 4a, 4b, 4c, 4d, 4e and 4f shows the process and equipment used during hot tapping. Hot tapping involves attaching an appropriate tee (T) section (figure 4d) through the use of bolts or welding unto an existing pipeline for hot tapping (figure 4e) after which a hydraulic sealed drill (figure 4a) is attached and used to mill a hole onto the live pipeline with the hot tap valve in open position (figure 4b). The milling of the pipeline is preceded with a pilot drill that will engage and prevent the part of the steel to be milled off from falling into the flow area (figure 4f). This is followed with the milling of the pipe for hot tapping. The hydraulic drill and cutter will then be retracted such that the isolation valve can be used to isolate the pressurised crude (figure 4c) before the removal of the drill and cutter (figure 4f) for the attachment of a new flow conduit.

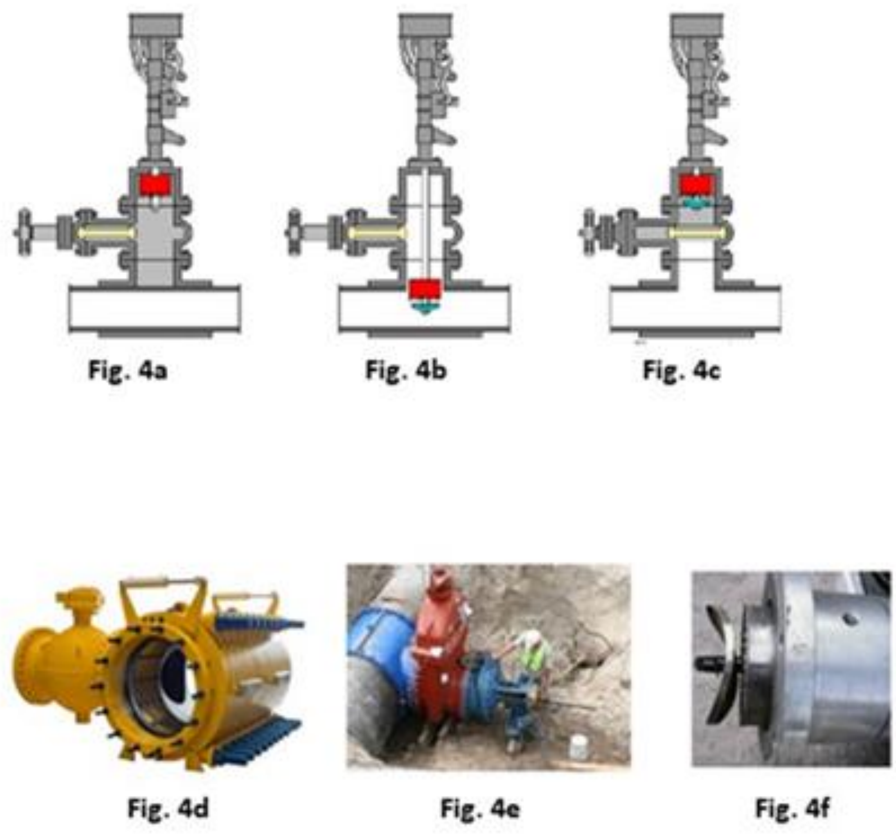

Figure 4. Hot tapping equipment and tools(Google 2016)

Once illegally tapped, the newly attached conduit could be used to steal crude for illegal export or for local refining. One of the early signals that some crude theft is ongoing is a comparison of the fiscal reconciliation of the total fluid received at the export terminal to the summation of all the crude pumped into the pipeline export route. The reconciliation factor (RF) would usually get close to 1.0 without leaks or crude theft but drifts away from 1.0 depending on the rate of leak or crude oil theft. Helicopter overflies are usually undertaken by operators to check for oil spills or recent soil excavations along the pipeline right of way (ROW) once there are indications, from consistent low RFs that some leaks or crude oil theft are ongoing. This non-routine surveillance overflies sometimes lead to spill as the thieves siphoning crude, in a bid to hide from the helicopter surveillance team, could leave the crude to flow out of containment as they drive off their tankers or tow away their storage barges at land or swamp locations respectively.

Crude oil leaks and thefts are used interchangeably in this research because until a proper investigation is conducted one may not know if the shortage recorded at the export terminal is due to operational leaks or whether they are due to crude oil vandalism through hot tapping. This interchangeable use will not affect the new process being proposed as it will be capable of identifying the location of leak or crude oil theft.

1.2 Research motivation

Crude evacuation loss of containment leads to deaths because of explosions. It also leads to soil and water pollution and fires whose compound effect could spiral into huge clean-up costs, loss of revenue, huge facility repairs and remediation costs. The act of continued pipeline vandalism is believed to have rendered some fields inoperable, thereby forcing some the international oil companies (IOCs) to divest from such hostile communities and lay off staff within the period 2000 - 2015.

This act of vandalism and crude oil theft have been reviewed and documented (The Guardian, 2013). *"Much of the stolen oil is exported to foreign refineries or storage facilities, says the report, including buyers in West Africa, the US, Brazil, China, Singapore, Thailand, Indonesia and the Balkans. The proceeds appear to be laundered through banks and other channels in various African countries, Dubai, Indonesia, India, Singapore, the US, the UK, and Switzerland. The scale of the 'bunkering' has shocked observers. Thirty-centimetre pipelines able to transport thousands of barrels of oil a day have been found leading straight from pipelines into the swamps"*.

The Guardian (2013) report estimates that the loss due to illegal oil theft in Nigeria amount to some £1bln per month. Another research by Delta non-government group Stakeholder Democracy Network (SDN) estimates that 75% of the stolen oil is being exported with the rest being refined in illegal "artisanal refineries". More than 500 of these refineries, according to the report, are known to have been set up in the last five years of report date, taking stolen crude and refining it into a rough diesel for local sale. According to SDN, a medium-sized illegal refinery costs around £3,000 to set up but can earn that back in a few weeks. But the operators need to pay hefty bribes to the police and military, as well as to buy oil tapped off the 1,600km of pipelines that cross the delta. Each tapping point, says SDN, can earn more than £500,000 a month but its investors must pay armed guards, the military, contractors, local communities and even oil company staff. Figure 5 is a typical loss of containment site abandoned by pipeline vandals with brownish vegetation, occasioned by environmental degradation, on both sides of the pipeline ROW.

Figure 5. Loss of containment fire from illegal tapping point (Anon 2016)

1.3 Reflexivity, positionality and research mind map

This research was approached from the perspective of a subsurface petroleum practitioner with some knowledge of hydrocarbon exploration and production practices in Nigeria and how similar operations are conducted at similar deltaic environments around the world. The issue of pipeline vandalism is related to lack of development or some legacy issues that turned the communities hostile and non-receptive to the IOCs operating in their land. It is recognised that many of the issues that Nigerians are struggling with exist only in Nigeria and hence researchers from other locations will struggle to understand why such situation exist in the first place. So, this dissertation is an effort at finding a technical solution to a local Nigerian problem. Some dialogue could even arise questioning the importance of this research work since the clamour for clean green energy in support to world climate change initiatives. Available data still suggest that environmentally and efficiently processed fossil fuels from crude oil would still be a part of the world energy mix for some years to come but most importantly that fluid transportation will be with man for as long as green gas would be transported from gas fields to LNG plants or our respective homes and industries where the gas are needed. Also, any product from this research will also apply to any form of fluid transportation system under suitable conditions.

There are several literatures on leak detection in urban water supply in big cities around the world. Some of these research focus on case studies while others are based on experiments. The urban water distribution networks, while like crude oil evacuation systems, are significantly different in terms of cost and impact to the environment. The health, safety, and environment (HSE) cases are different because loss of water containment in water pipes would lead to unintended irrigation as the water will be useful to the field where it is leaking through the provision of luxurious greenfield at appropriate whether condition. On the other hand, crude oil is inflammable and could ignite to cause explosions, fires, and deaths during any loss of containment situation. Also, almost every house or group of houses in a proper water pipeline network has some metering system, so monitoring leaks is easier when compared to crude oil transport over an area of 75,000sq. km with only a few crude oil flow measurement points. Thirdly the only known motivation for stealing water would be to save a few Pounds Sterling a month where successful, but crude oil theft would lead to huge financial gains. There are also lots of business controls that could deter any potential water thief because the hurdles to be surmounted are huge and could have some cost implications which would require a long payback period. Estate developers usually are required to apply to other organisations for supply of water, gas, electric, telephone services etc., and the home buyer gets a home with several contracts from these service providers who already installed controls for their services. In other countries, major trunklines are surface installation but in Nigeria, such trunklines are buried. Even the flowlines that were originally surface were buried as a deterrent, but this did not stop the vandalism. According to shell, crude oil theft on the pipeline network resulted in a loss of around 11,000 barrels of oil a day (bbl/d) in 2018, which is more than the approximate 9,000 bbl/d in 2017 and since 2012, SPDC[1] has removed more than 1,160 illegal theft points (Shell Nigeria, 2020).

Notwithstanding all the above, this research aims at providing a solution that could apply elsewhere if this unfortunate situation manifests in such environment. In other to highlight and address all issues relating to crude oil theft in Nigeria, a research mind map was created as shown in figure 6.

[1] Shell Petroleum Development Company (SPDC) is a Shell Operated Joint Venture Company between Shell and other companies in Nigeria https://www.shell.com.ng/

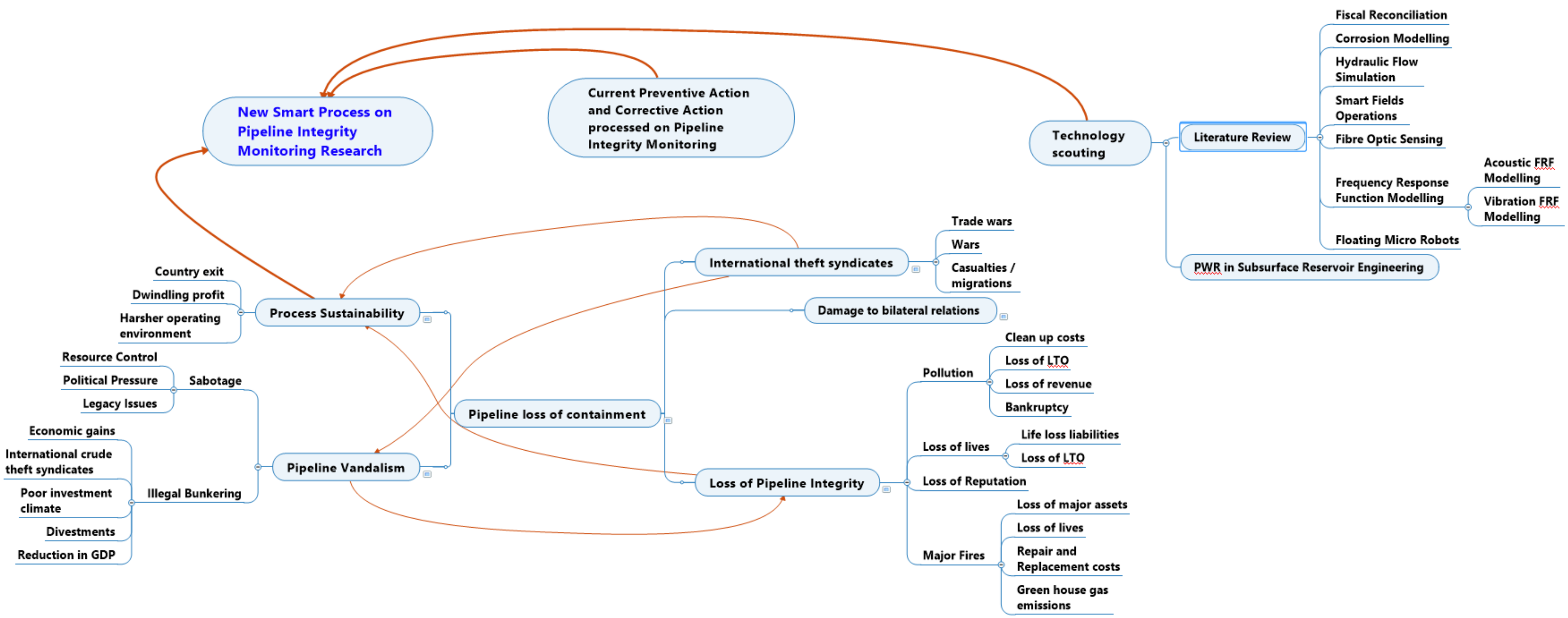

Figure 6. Research mind map

The continued crude oil theft and its associated devastating economic and environmental effects is an indication that the current reliability assurance process that relies on PM and CM actions, whether through design or monitoring, needs improvement in the Niger delta. As a result of the market created for stolen crude, this sub-optimal operating environment becomes more difficult to stop. This is because the international buyers are continuously demanding stolen crude and the pipeline vandals, or their intermediaries use the proceeds from this trade to sponsor the already armed vandals with more sophisticated weapons for the continuation of oil theft business in Nigeria. This operating environment is not sustainable and has had significant impact on the IOC operating bottom-line and has continually forced such companies to continually divest from valuable but non-operable assets. This situation creates continuous downward developmental spiral, environmental degradation, and continual underdevelopment for Nigeria.

A recent study commissioned by Royal Dutch/Shell put the amount of oil stolen each year by pipeline vandals in Nigeria at between 100 million and 250 million barrels. At an average of US$60 per barrel then, this translates to a loss of about US$15 billion each year (Mumuni & Oyekunle, 2007). This report is in full alignment with the Guardian report (2013) that estimates that the loss due to illegal oil theft in Nigeria amount to some £1bln per month then.

1.4 Research Aims, Objectives and Impacts

1.4.1 *Research aims.*

This research aims at providing a technical solution that will lead to early detection of crude oil theft or leaks. The use of mechatronics discipline and artificial intelligence workflows were investigated and where suitable used in crafting a solution for this research.

Mechatronics engineering could be viewed as modern mechanical engineering design in the sense that the design of a complete mechanical system are performed together with that of electronics as well as computer controls (Waterloo, 2017). The mechatronic science involves the use of sciences or engineering principles in the provision of engineering solutions to identified products or processes. Artificial Intelligence workflow, as it relates to crude evacuation through pipelines, could involve the use of the pipeline flow characteristics or some of the environmental data surrounding the pipeline being studied to determine leak points and leak rates. This research aims at providing a technical solution that will aid the IOCs in recovering their developed hydrocarbon with minimal losses due to pipeline vandalism. This could be achieved through the provision of early warning system about ongoing hot tapping where possible or providing, within a reasonable time, information of ongoing crude theft and hence rapid response for assets safeguarding operations.

1.4.2 *Research objectives*

The objectives of this thesis are as follows:

1. To scout literature for potential technologies that could be used for monitoring and detection of crude oil theft and leaks in pipelines.
2. To verify suitability of collected data and where appropriate conduct computer modelling for extra data generation.
3. To use available and generated data for model creation, testing of proposed solution and verification of useability of proposed solution.
4. To recommend a solution or new process for pipeline leak detection and leak rate estimation.

1.4.3 *Research impacts*

The achievement of the proposed research objectives will:

- Contribute to safeguarding lost revenue to the government and people of Nigeria which is currently estimated at £1bln per month.
- Contribute to improved HSE performance that could lead to reduction of lives lost due to loss of containment explosions which was estimated at over 1000 people within the period 2004 – 2014.
- Contribute to the reduction of greenhouse gas emission from illegal refineries which currently are not fully quantified.

1.5 Thesis structure

The process and reasoning that eventually led to the discovery of a cost-effective solution to crude oil leak (or theft) identification and quantification during pipeline crude evacuation in the Niger delta is discussed below.

- Chapter 1 highlights the case for action considering the quantity of crude oil stolen from major international operating companies (IOCs), its crippling effect on the Nigerian economy, and how these theft operations sometimes lead to loss of containment explosions, deaths, pollution, and greenhouse gas emissions. This research was approached from the perspective of an oil and gas practitioner who tries to compare hydrocarbon production evacuation practices and challenges in Nigeria with that of similar deltaic environments around the world. This necessitated some discussion on reflexivity, positionality and research mind map which addressed questions about the importance of this research work since the current clamour is for clean green energy in support to world climate change initiatives. The reflexivity, positionality, and research mind map documentation was followed with the research aims and objectives and this chapter ends with an outline of proposed thesis structure which aims at scouting available literature for potential technologies that could be used for the development of a new process for crude oil theft detection and leak rate quantification.

- Chapter 2 is a process documentation for the selection of a research philosophy that could progressively address the research objective and all potential issues relating to crude oil theft in the Niger delta in a structured methodology. A Venn diagram was used to highlight some philosophical perspectives and how they could be used to select the required research strategy for the knowledge sought. If knowledge is being sought, as in this dissertation, for ways of improving pipeline integrity monitoring then we must consider the feasibility and viability of all conceivable options. It is only when our desire fuses with the feasibility and viability attributes that an innovation is created. The adopted research process is pragmatic epistemology which arrived at a new knowledge through deductive reasoning. The research hypothesis was a postulation that "If we have a way of continuously measuring the steady state conditions of a given pipeline at regular intervals (say 5 or 10 km) during operation, then we could, through deviations trending from the steady state operation, determine the point of leak or crude oil theft and quantify rate of leak or crude theft. Having crafted a plausible research hypothesis, some efforts were made on how to use available data for testing of the crafted hypothesis such that where such testing is possible the scientific testing process can be used to support the documented research hypothesis through deductive reasoning. As an introduction to the literature review, this chapter documents a research domain which must be constrained by the fact that there is continuous hydrocarbon flow in trunklines. This therefore implies that any technology for leak detection should not demand production interruption otherwise this would require design changes and difficult to operationalise.

- Chapter 3 is a literature review of potential technology solutions that could address the research objective within the pipeline transport constraints. A considerable discussion on the problem statement was presented here as an introduction. This was followed with a discussion of hazard and effects management process (HEMP). HEMP is a risk management process that is used to install a set of barriers to top events (incidents or accidents) and where such events have occurred, due to failure of installed barriers, uses another set of barriers to prevent escalation. The three ways of managing known risks based on the HEMP process are : 1.) Reject risk, 2). Transfer risk or 3.) Accept and manage risk. The demand for petroleum and natural gas, which accounts for one third of total energy supply needed to support human development through the provision of vital raw materials for habitation, medication, transportation and industrialization cannot be ignored hence we must accept the loss of containment risks and find ways of minimising its associated risks. It is hoped that this research will strengthen the crude evacuation HEMP process by adding either a control barrier or a recovery barrier in the management of loss of containment during crude evacuation process. This HEMP discussion was followed with literature review of potential technologies that are capable of providing potential solution to crude oil theft problem. The list of internal and external technologies reviewed include fiscal reconciliation; corrosion monitoring; flow simulation; smart field operation; fibre Optic sensing; frequency response function modelling using acoustic or vibration, and floating micro robots. The strengths, weaknesses, and suitability of these reviewed technologies were used to arrive at some conclusion of potential technologies for progression to testing of research hypothesis.

- Chapter 4 builds on the conclusions of the literature review to select suitable technologies for pipeline leak detection based on research process of using deductive reasoning to see if available data can support the documented research hypothesis. The concept selection exercise was to ensure, among other things, that the conclusions of the literature review have, within the trunk line operational framework and boundary conditions, scanned wide enough to identify all potential technologies for the achievement of research objective for leak monitoring, crude oil theft detection, and quantification of leak (or crude theft). The evaluation criteria include ability to detect leak; ability to detect pilferage; ability to estimate rate of leak; ability to detect hot tapping locations; continuous data acquisition suitability; suitability to trunkline operating environment (OE); technology maturity; ease of repair and troubleshooting. This evaluation exercise yielded smart operations as the most favourable technology. Unfortunately, the smart operations is unable to detect hot tapping operations. Acoustic emission modelling and vibration modelling were assessed as the only technologies capable of detecting hot tapping operations. This notwithstanding smart operations was selected and progressed for further studies to close its operational gap. This chapter ends with smart fields operation synoptical documentation where the smart fields operations nomenclature as used in this thesis were explained. The basis for smart fields operations and digital twin is simulation and there are several levels of smartness or smart operations capability. This chapter ends with a documentation of smart fields operations technology progression path which highlights the details of explored options for the development of a solution for leak detection. As contained in smart pipeline operational requirement, the pre-leak data prognostic method and the post leak data diagnostic methods were discussed.

- Chapter 5 focuses on how to close the feasibility gap on using smart operations technology. As with most research efforts we have an idea of what a technology solution could be but the pathway to this solution, if eventually achievable, is only attained through some doggedness.

This dissertation, which eventually delivered a new smart process for pipeline integrity monitoring, followed a rigorous but sometimes flip-flopping map on technology leads as documented in the solution pathfinder mind map which formed a part of this chapter introduction. Two separate approaches to using smart operations technology to achieve this research objective which were highlighted in chapter 4 were discussed in detail. One approach would be to start with a hypothesis and then test such hypothesis using observed data to see if observed data follow some trends as proposed in the hypothesis. The other approach would be to theorize on observable patterns, then test available data for conformance and where appropriate create a theory or hypothesis. The main difference between these two methods is that one is based on post-leak processed data while the other is based on pre-leak processed data. In pre-leak processed data methodology, the analysis focuses on events that could be assessed to have happened before a particular result is achieved. For example, you need to have punctured a pipeline before a leak could be established. In post leak processed methodology, we focus on results to determine the preceding events. Applying post leak processing methodology, we could say that if there is a leak on a pipeline it means that the pipeline must have been punctured. Post leak data processing is instantaneous instrument based and requires that we have some knowledge of what is flowing while pre-leak processing is based on artificial intelligence knowledge of past events and data surrounding the pipeline being investigated or a similar pipeline. The organized event data which influence pipeline leak, based on pre-leak processing are non-existent or difficult to generate in the Niger delta and hence makes the use of pre-leak processing methodology difficult. Post leak processed analysis methodology seems promising since it is based on instantaneous measurements. Unfortunately, only limited measurement capability exists along most trunklines and this makes the use of the available Niger Delta data unusable in post leak processing analysis. Machine learning (ML) was introduced as a potential third AI method for leak position and rate estimation during fluid evacuation. However, ML algorithm for leak point detection was assessed as potentially luxurious as such experimentation would take an unsustainable long time to train. It was therefore decided that the use of ML is not suitable as a third option for leak evaluation during crude oil evacuation. Rather such ML workflow could be used to improve any System Descriptive Model (SDM) developed using pre-leak or post-leak data. This therefore meant that there is need to re process the available data for use in creating a new process for pipeline integrity monitoring based on post leak data processing in support of research objective.

- Chapter 6 compares options for the generation of the required data in support of smart operations workflow for leak detection and quantification. One option could be by laboratory experiments to generate the required data while another option could be the re processing of available data through computer simulation. The cheaper alternative process involving the use of computer simulation was selected, instead of laboratory experiments based on extremely limited cost and time resources. The research basis for design discussed our knowledge of isothermal mass flow in a confined space which requires knowledge of Pressure, and volume at any given position to describe a flow domain. However, having discounted the requirement for in-line volume measurements research was now reduced to capability to monitor pipeline leak position and rate through pressure measurements only. This chapter ends with the basis for the selection of PIPESIM computer simulation software which is one of the best flow simulation software used by oil and gas exploration companies around the world.

- Chapter 7 starts with a review of existing trunkline systems design in other to generate a representative detailed design requirement for leak investigations. Models of a trunkline and a delivery line case were created for leak simulation experiments. The first set of experiments showed that leak detection is possible through monitoring of pressure differentials. Our capability to further refine the results of these experiments or extend this finding to a universal pipeline integrity monitoring was further studied. The results demonstrate that for a given pipeline with evenly spaced pressure measurement opportunities, we could use the pressure variations from these pressure measurement points to determine the point of crude leak or theft from any section of the trunkline. This results conditionally support this thesis hypothesis and was further studied for universal application.

- Chapter 8 validates the use of pressure gradient in leak detection having demonstrated that monitoring of pipeline pressures at a few pressure nodes is just sufficient for leak detection. Additional experiments were executed to fully quantify the relationship between known influencing parameters like flow volume and conduit size on the rate of change of pressure per unit distance during crude transportation. This theoretical basis was for the use of pressure gradient for leak detection based on analogous comparison of subsurface reservoir engineering practice of using fluid gradients to determine fluid contact planes as well as using reservoir pressure depletion to determine the total produced volume from a reservoir whose size is well known. An attempt was made on presenting the relationship between pressure gradient and volume flow rate in pipes for steady state incompressible fluid using Navier Stokes equation. The results of the PIPESIM simulation experiments agree with the relationship between flow rate and pressure gradient derived from Navier stokes equation.

- Chapter 9 focussed on the use of data analytical methods to augment pressure gradient analysis methodology which has already been proven as useable in leak detection. Two analytical methods for estimating leak rate in any pipeline evacuation system were verified. The first set of analysis which is based on algebraic equations of pressure gradient line and determination of line intersection points demonstrated that the use of gradient method is effective in multiple leak detection in any pipeline system. This approach would however need to be augmented to be able to assign the leak rate to the respectively identified leak points. The second set of experiments used the concept of angular vector depression or relaxation method to propose another solution for leak detection. This approach was also effective in predicting both the point of leak as well as the leak rate in a single leak situation. It was therefore conceived that a combination of the intersection method and the angular vector relaxation method could be combined and used in the identification and quantification of multiple leaks in any future pipeline system. The enclosed angle vector relaxation (EAVR), which was a discovery during pressure vector manipulation, due to leak was verified as proportional to the rate of leak and hence was documented as a necessity for pipeline leak characteristic curve documentation upon which this recommended new process is based. The use of pipeline system descriptive model (SDM) or pipeline leak characteristic curve was investigated, and the results were outstanding for multiple leak investigation. This new finding was therefore documented as a concluding confirmation to this dissertation that: If we have a way of continuously measuring the steady state conditions at regular intervals (say 5km or 10km) on any pipeline during operation, then we could, through deviations trending (or monitoring) from the steady state operation, determine the points of leak or crude oil theft and the corresponding leak rates. This chapter ends with a discussion on the practical implementation of the proposed smart process for pipeline integrity monitoring like uncertainty management and the pipeline digital data acquisition process. Having demonstrated the documented research objective, as well as recommended some additional recovery barriers for the management of loss of containment in the crude oil evacuation HEMP process, marks the end of this dissertation but some further research for reprocessing of fluid flow processes were undertaken for this new knowledge extension of the recommended EAVR process into inflow analysis. The difference between leak and inflow within any space or domain is sign convention. Leaks represent some fluid outflow from a defined domain while inflow represents some fluid movement into the given domain. As a result of this, it is believed that any technology that can be used to detect leak can also be used to detect inflow: hence some further experiments to test the applicability of the demonstrated EAVR into inflow prediction.

- Chapter 10 is a further verification of one of the research finding for leak and inflow estimation using enclosed angle vector relaxation method. The proof of this new concept was based on pressure measurements for estimation of transmission pressure gradients for the determination of leak rates at identified leak points. Once the leak points are identified, the same pressure gradients used in the identification of leak points can also be used in the estimation of leak rates by comparing pre-leak pressure gradient vector and post leak gradient vector and the angle between them which has been defined as enclosed angle vector relaxation (EAVR). In the graphical proof of concept documented at pressure gradient vector analysis it was felt that this EAVR can be used to estimate fluid inflow in addition to leaks. This sounds logical since the difference between inflow and leak is that one is opposite of the other in sign convention within the domain space being studied. This corollary was tested through two case studies in subsurface engineering. These additional tests on the capability to extend the use of EAVR process as a universal concept for predicting leak and inflow during fluid evacuation in conduits is now proven and is therefore recommended as part of the smart process for pipeline integrity monitoring.

- Chapter 11 is a documentation of the progressive research conclusions that led to the new process on pipeline integrity monitoring process and possible steps on how to design some computer algorithm that will automatically run the process with minimal human intervention in line with artificial intelligent workflow. The new smart process for pipeline integrity monitoring involving: data acquisition; data baselining; leak point determination and leak rate quantification has been developed and proven as capable of detecting multiple leaks (and inflows) and quantifying the rate of leak (or inflows). A documentation of the conditions for the validity of proposed new process for pipeline integrity monitoring was also made and this chapter ends with some recommended further research areas for the perfection of proposed new process. Specifically, this dissertation concludes that the EAVR concept, which is one of the main contributions of this research: is a new knowledge addition to Physis and Fluid Mechanics; is also a discovery, and a process invention.

2 RESEARCH METHODOLOGY

2.1 Introduction

This dissertation is focussed on process safety improvements during hydrocarbon transport from gathering stations to the point of export or use. The philosophical questions being addressed in this dissertation are focused on how to stop or minimize the effect of crude oil theft in Nigeria.

This chapter discusses the process for maturing thoughts into innovation and in so doing selects the most suitable research method for the achievement of the research objective of predicting and quantifying crude leak or theft during crude evacuation in trunklines.

2.2 Pathway to knowledge innovation

Our aspiration is to get to an operating environment where any pipeline operator will know within reasonable time when and where crude oil stealing is ongoing so that they could act before the crude oil theft will lead to explosions, environmental degradation and deaths. The process of getting from the current operating climate in the Niger delta to our desired operating climate would be our research strategy and any of the available research methods that requires minimal effort would be adopted as our research strategy.

A Venn diagram is shown in figure 7 to highlight some philosophical perspectives and how they could be used to select the required research process for any knowledge innovation. If knowledge is being sought, as in this dissertation for ways of improving pipeline integrity monitoring then we must consider the feasibility and viability of all conceivable options. It is only when our desire fuses with the feasibility and viability attributes that an innovation is created. The innovation sought could as well be an improved way of executing an old activity or process. Ideas are created when concepts are conceived and articulated to address a desire. The philosophical questions on these ideas would include whether we know what we seek, whether it is possible and whether it can be proven. We could also ask questions like whether we know what we are getting into? These set of preliminary research questions are necessary to avoid starting a white elephant project: wasting a lot of resources without taking off. Getting this framing stage right is necessary and could involve a lot of iteration and idea refinements. These set of initial work is called frontend loading in business enterprise and is critical because experience have shown that getting it right at framing stage would make it easy to fully achieve project objectives once the project has progressed to detailed design stage. Attempting to force-fit a product outcome into a wrongly framed project usually results in exponential cost and time overruns. Framing therefore should be wide and divergent to accommodate all foreseeable solutions. One could just imagine having a busy airport, like Heathrow, which never imagined that there could be jet planes like Airbus 380 or Boeing Dreamliner that would need a longer runway in the twenty first century.

Inspiration could be organically evolved, or it could be external to the problem being solved. External inspiration could manifest from analogues, which could be some proven processes in other environments. Most literature reviews are aimed at gaining insights from internal and external inspirations and it is a collection of these potential practices worth replication that creates a sphere of feasible options for idea realization. Some of these realizations would be assessed as technically feasible while others would require a lot of energy and resources to reduce the remaining uncertainties to their target solution to as low as reasonably practicable (ALARP). The ALARP stage in any development represents a situation where you need to invest a lot of resources to achieve very minimal improvement in project objective.

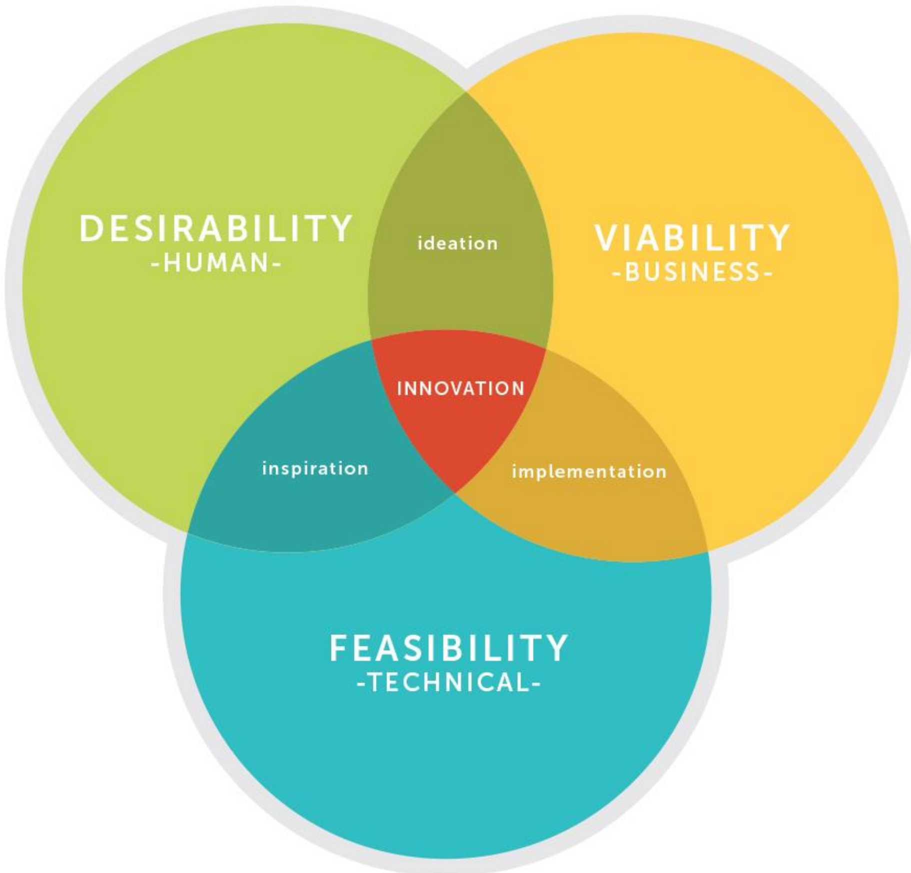

Figure 7. Innovation Venn diagram (The framework bank, 2016)

Viability is evaluated based on value and the value adds most times is directly related to economic gains which are easily measurable. Values could also be based on alignment to organizational goals which may not be easily measurable, hence even when the economic gains are not obviously greater than employed cost, sometimes decisions on project progression could be based on strategic vision alignment. How do you evaluate research viability? Research could be based on 1.) Desperation, or 2.) Efficiency improvements. It should be noted that improvements in human habitation on earth has always been a routine product of research based on continuous improvement. Once an innovation has been established it becomes routine or taken for granted while improvements are built around it. E.g., until the discovery of electricity man lived within the confines of day and night as dictated by the sun and the moon. With the discovery of electricity came inventions like electric light, radio, and television (TV) and someone can have twenty-four (24) hours without darkness. Several consumer-electricity based research are now focused on picture and sound quality improvements, which is now the selling point for most consumer product companies marketing TV and Radio electronics. The year 2020 was a year where activities around the globe were halted for the first half of the year due to Corona virus (or Covid-19) pandemic. Almost every country was directly or indirectly involved in data collection, experimentation, or fighting through some form of research for innovation on how to stop the Covid 19 virus. This type of research is based on desperation to reduce mortality effect of the pandemic. Space research and its derivatives like 5G information, technology and communications (ITC) process could be considered as products of efficiency improvement research. So where do you classify research on crude oil theft in Nigeria. Most Nigerians would classify such research as that of desperation based on Research motivation discussions. Europe and America would also classify that local research as that of desperation primarily because such operation will destroy the Nigerian economy if not addressed and a product of such failed economy of the most populous African nation would lead to increase in illegal migration to Europe and America.

The fact that the crude evacuation or the hot tapping process generates data implies that we cannot divorce the data generation process from the crude oil evacuation process hence this type of arguments for demonstration of truth would influence the research method that would be adopted for this research.

2.3 Research method

One branch of philosophy which is concerned with the theory of knowledge and its relationship to concepts such as truth and beliefs is known as Epistemology while the other branch that focuses on what can be known and how it can be known is Ontology (Holm 2016). Ontology is traditionally classified as metaphysics and deals with questions concerning what entities exist or may be said to exist and how such entities may be grouped, related within a hierarchy, and subdivided according to similarities and differences (Wikipedia, 2020). On the other hand, Epistemology, which relies on objective facts that have been established and can be demonstrated (Research Methodology, 2020), is the systematic or logical investigation of three fundamental questions: What is knowledge ?; Can we have knowledge? and How do we get knowledge? (MESA COMMUNITY COLLEGE, 2020). An attempt is made at selecting a research philosophy that could generate a technology solution capable of reducing deaths due to crude oil explosion from pipeline loss of containment during crude theft. A primary research, like this dissertation involves collecting data about a given subject directly from the real world (Dana Lynn Driscoll, 2017) and, as discussed in Pathway to knowledge innovation, we have some idea of what improvements we need, so Epistemology was adopted as a research philosophy for the new knowledge sought.

So, can we have the knowledge and how do we demonstrate that the knowledge is achievable. The use of mechanical observations, computer simulations, and laboratory experiments were considered data processing options in support of this primary quantitative research based on epistemology. Some form of secondary research methodologies in the form of literature review, which is a form of qualitative primary research, of current technologies for pipeline leak detection were undertaken. The terms used to describe epistemological positions vary, depending on whether it is describing the origin or the acquisition of knowledge. A brief overview of the epistemological options is presented in Figure 8 (University College Dublin, 2020).

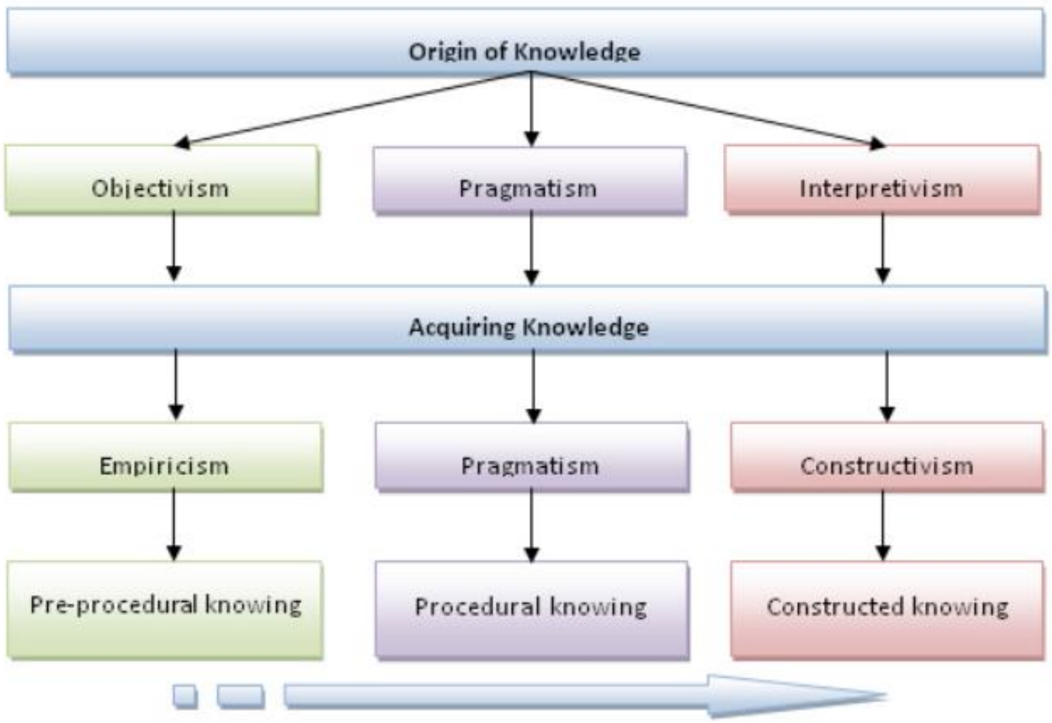

Figure 8. Epistemology and learning theories (University College Dublin, 2020)

Some of the philosophical orientations in epistemology were discussed by Holm (2016) who documented among other things that: the Positivist approach stipulates that the truth or cause can be found, tested, and verified by scientific standards; an Interpretivist approach would seek a subjective understanding of the objective truth, assuming that the truth is shaped by the viewers' perception and understanding; the Pragmatists approach states that instead of focusing on the methods to use, the researcher should emphasise the problem or question at hand and use any available approaches to understand the problem. But there are other orientations as shown in figure 8 and by other researchers who suggest that the applicable orientation depends on the problem being solved. "Pragmatism is a deconstructive paradigm that advocates the use of mixed methods in research, 'sidesteps the contentious issues of truth and reality' (Feilzer 2010, p. 8), and focuses instead on 'what works' as the truth regarding the research questions under investigation (Tashakkori & Teddlie 2003b, p. 713)" (Rayed AlGhamadi, 2020).

The pragmatism or pragmativist approach was therefore selected because research involves some mixed research methods as earlier explained and builds on earlier acquired knowledge. Pragmatic epistemology assumes that (Romania, 2013): “1). Truth is the product of a dynamic, negotiated collective agreement; 2). Therefore, there is no final, certain and objective knowledge to be unveiled. Pragmatists conceive knowledge as a contingent, fallible, and operational human activity, oriented to social practical purposes, defined by the community and 3). Structures are always the contingent and partially unpredictable product of a process of interaction between factors or individuals. The idea of pre-existing, transcendental and immutable structures—in the natural, social, and theoretical world—are considered as artificial social constructions”.

The fact that pragmatism or pragmativist philosophical orientation can be built on a hypothesis makes it more attractive such that the result of testing such hypothesis could determine the new knowledge or world. The pragmatic epistemology was therefore used for testing a suitable hypothesis that could be used to achieve the research objective of monitoring crude theft or leak. The new knowledge being sought now is reduced to pipeline operational activity that could be tested for confirmation of loss of containment. The RF is a manifestation of loss of containment, but this is just a signal that calls for more investigation about the points of leak and the respective leak rates. So, is there a way of checking loss of containment in pipelines during crude evacuation process?

Can this pragmatic epistemological approach be used to investigate the hypothetical postulation that:

> ***If we have a way of continuously measuring the steady state conditions of a given pipeline at regular intervals (say 5 or 10 km) during operation, then we could, through***

deviations trending from the steady state operation, determine the point of leak or crude oil theft and quantify rate of leak or crude theft.

A demonstration of this new world is the knowledge sought.

Pragmatism deals with the analysis of concepts and the practical implication of our choosing to take a concept to have a certain meaning over another. The tough-minded pragmatist believes in posteriori and empirical learning and believes that something must be proven before it can be said to be known. We need to look at the practical consequences of belief as well as context before choosing what to believe. According to James and Charles Sanders Peirce[2] in discussion of James Williams pragmatist philosophy, what we come to agree on through a process of investigation becomes the truth. There are always disagreement about what is the truth so if pragmatism is to fulfil its goal, it needs not to tell us that agreement is the answer but how to resolve any disagreements (Carneades.org, 2015).

So, can we have the knowledge and how do we demonstrate that the knowledge is achievable. There are several orientations of pragmatist epistemology and challenges on the concept of truth: whether it is a negotiated agreement or whether it is one individual's belief that makes one happy. One of the world's topical issue during the conclusion of this research in 2020 is the vaccination of people around the world against the Coronavirus. Is the vaccination to protect one against the virus or is it to give some protection against the virus or is it to give the receiver some sense of protection against the virus? Each of these three beliefs means different things and there are elements of truth in each of these perspective truths. Scepticism will give each of these a different interpretation and so is the paradigm shift pragmatist. Pragmatic epistemology is about a process for believing what is true.

[2] Charles Sanders Peirce (1839–1914) was the founder of American pragmatism

Science has a procedure of investigation and will in due course determine which of the views of the reason for vaccination is indeed true.

The process of discussing project feasibility yielded smart operations. Learnings about objects from the pragmatist cannot be divorced from the objects themselves. The truth sought (about this new process) was therefore reduced to what we can learn from the pipeline, or its immediate environment during crude evacuation process. Is there a way of testing the research hypothesis which states that if we can monitor the steady state conditions in a pipeline during crude evacuation at regular intervals, then we can determine the point of leak? Electromagnetism was severally used as an analogue to demonstrate how this truth can be supported using pragmatic epistemology. Having a core metal, a coil and a current source does not produce an electromagnetic effect until the coil encases the metal and there is current passing through the coil. Also, it is only when all the crude passing through the pipelines are not received that we can suspect leak or crude theft.

So how can we know the point of crude oil theft when it is proven that indeed there is a theft? We can use the transmission fluid parameters like pressure to identify leak points and we can also use the activities within the near environment of the pipeline to estimate the probability of leak at a given point. These two approaches are based on deductive reasoning and inductive reasoning respectively. According to Jeremy Donovan "By its strictest definition, inductive reasoning proves a general principle — your idea worth spreading — by highlighting a group of specific events, trends, or observations. In contrast, deductive reasoning builds up to a specific principle — again, your idea worth spreading — through a chain of increasingly narrow statements." (OutRespectiveWritting2019, 2019).

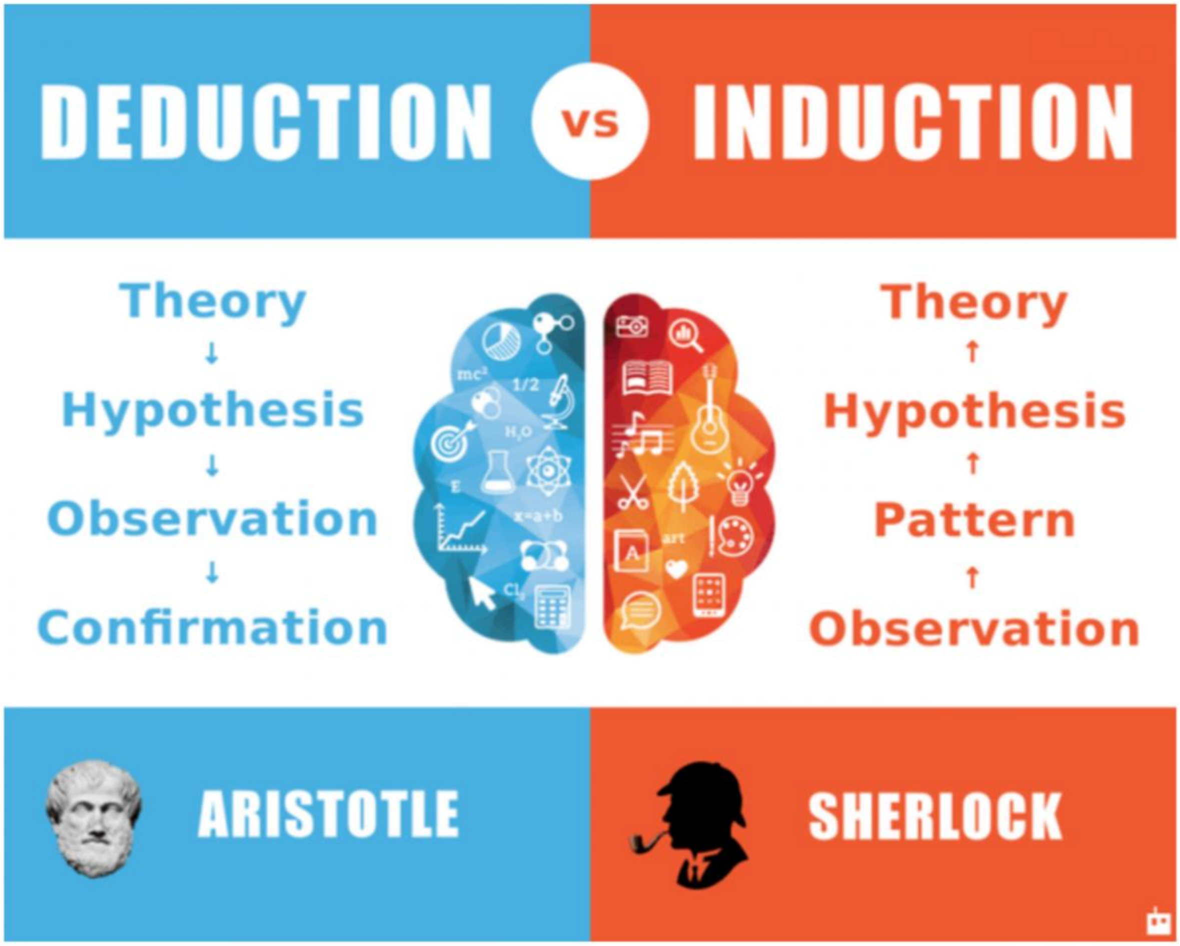

Figure 9. Deductive Vs Inductive reasoning (OutRespectiveWriting, 2019)

Figure 9 documents the thought flow process for deductive and inductive reasoning as could be applied to pragmatic epistemology as well as highlight the champions of the respective approaches. Both thought processes uses some form of hypothesis and could be applied to this research on crude oil detection process.

Attempts were made at proof of the published research hypothesis through the pragmatic epistemology using either the deductive or inductive logic. The first attempt was using inductive logic for prognosis of leak point. This environmental data analysis methodology focuses on all potential external incidents that must have happened as a precondition for any expected outcome to occur. In the case of crude oil theft or leak, this focused on activities external to the pipeline being investigated that needs to have happened to create a variance between the total crude being received at the terminal and the total crude being pumped from the respective flowstations. Potential activities that will lead to crude oil theft or leak include operational leaks and pipeline vandalism for the purpose of creating leak or crude tapping point. This pre-leak prognostic data processing workflow feasibility was evaluated using causal reasoning and artificial neural network (ANN) both of which are artificial intelligence workflows. The ***observations*** for this approach would involve studying logic, and inferences to see if they correlate with data influencing crude theft. The events which influence pipeline leak, based on pre-leak data prognostic processing has been documented as: terminal reconciliation factors; loitering along pipeline ROW; employment indices; growth of illegal refineries; automotive activities close to pipeline ROW; periodic petroleum product shortages. These data are difficult to generate in the Niger delta and hence makes the use of pre-leak data prognostic processing methodology difficult. The aim of such study was to create a ***pattern*** that could be used to test the research hypothesis so as to create a new ***theory*** or model called SDM for prognosis of leak points.

A second analytical attempt using deductive logic for leak diagnosis using post leak data was evaluated. Central to the support of this post-leak data diagnostic process was pressure ***observations*** for estimation of transmission pressure gradients for the determination of leak points. Once the leak points are identified, the same pressure gradients used in the identification of leak points can also be used in the estimation of leak rates by comparing pre-leak pressure gradient vector and post leak gradient vector and the angle between them which has been defined as enclosed angle vector relaxation (EAVR).

2.4 Research process

This pragmatic epistemological research process, based on the forgoing, is based on deductive reasoning as shown in the research process depicted in figure 10.

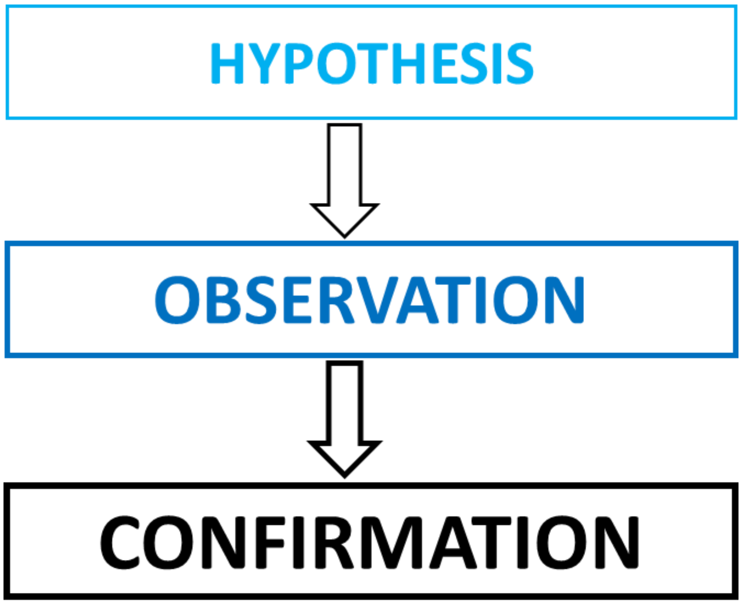

Figure 10. Research process

Having crafted a plausible research hypothesis, some efforts were made on how to use available data for testing of the crafted hypothesis and where such testing is possible the scientific testing process shown in figure 10 can be used to support the documented research hypothesis.

2.4.1 *Research hypothesis*

The objective truth sought in this pragmatic epistemological research should be supported if we are able to investigate the postulation that:

> ***If we have a way of continuously measuring the steady state conditions of a given pipeline at regular intervals (say 5 or 10 km) during operation, then we could, through***

deviations trending from the steady state operation, determine the point of leak or crude oil theft and quantify rate of leak or theft.

2.4.2 *Data based observation.*

The importance of data in modern engineering cannot be over emphasized especially with respect to HSE. The first set of automobiles from Daimler Benz around 1885 or the later versions of the early 20th century had very minimal HSE instrumentation. It was important then to have a functional vehicle that could move and stop safely as required. Even up to mid-20th century only basic improvements in operational data like the quantity of gasoline in the gasoline tank and the speed of travel were judged to be sufficient. Around early 1980s some of these automotive instrumentations improved such that the fuel endurance could be estimated by integrating the specific fuel consumption of any given automotive and the respective instantaneous speed for the given vehicle. This innovation led to improvements in human comfort and automotive efficiency in addition to HSE considerations as the vehicle then were able to advise the driver if there is enough fuel to undertake any desired journey. Extras like cruise control, safety airbags, automatic suspension dampers, and automatic air-conditioning are mechatronic processes that were added later to make the automobiles more comfortable. With the development of the GPS, more innovations were added such that the car would now additionally inform the driver of the position of the nearest fuel filling station for fuel top up if the available fuel is not enough for the planned journey.

The act of crude pumping generates data in the form of pressures, volume flow, and temperatures during the transport process. The chemical properties of evacuated crude as well as the presence of impurities like CO_2, H_2S and sand has some influence during the transport process. The crude transport data are continuously generated at two stations: the flowstations and at the terminal. These data are manually stored and used to compute monthly reconciliation factors. The question now is whether there is room for improvements on current data collection and analysis process. One easy improvement would be to increase data intensity by increasing the data acquisition points along the length of the trunkline and this has been evaluated as very useful. Like the automotive analogy explained earlier, handling and processing of the collected data is an essential part of any fluid evacuation data management process. Data could be manually processed and used to make decisions which would be implemented by operators. Unfortunately, there is always a lag in implementation time and sometimes huge demand on staff resources if manual processing is employed considering the spread of trunk lines. This dissertation is focused on continuous measurement and observation of the steady state conditions of nodal observation points of a given pipeline during operation and this could not be effectively achieved via manual data gathering and processing. The use of an electronic system that screens data streams, selects data based on pre-set sampling frequency, validate data, and uses some logic to continuously advise operators on the state of the pipeline integrity was therefore suggested. The most important data for this deduction based on post-leak data based diagnostic process is the *monitored* transmission pressures which can be measured with an appropriately sized transducers and transmitted through any suitable IoT system to the data digital processing centre for use in leak prediction.

The data evaluation process could be as simple as trend monitoring with preset trigger points that could use the traffic lighting system to advise operators on the state of the sections of the pipeline being monitored. This could also involve continuous monitoring of expected results based on process inputs. Depending on the data evaluation method, research result could be a qualitative assessment or a quantitative one. This research is based on quantitative assessment as the research objective is to identify leak point and quantify the crude oil leak rate or theft. As a result, the data processing methodology, which could involve input from several sources should be such that the results of some form of continuous analysis, based on data *observations*, could be used to identify leak point and quantify the crude oil that is leaking or being stolen.

2.4.3 *Confirmation of hypothesis*

Computer simulation experiments were designed and executed for data re processing. The data reprocessing was to generate intermediate pressure points for use in the testing of the hypothesis which was reduced to the research question of our ability to monitor leak through pressure measurement only. The results of the several experiments were progressively converging and eventually led to the use of vector methods for analysis of experimental results.

Smart operations, as documented in section 4.2: Technology concept selection report page 97 was selected as a technology concept that could be used for the detection and quantification of leaks during crude evacuation. As discussed in synopsis of smart operations (page 101) the post leak data diagnostic method was eventually deployed using vector algebra as developed in section 9.3 on Pressure gradient vector analysis page 176 and selected for the development of the new smart process for pipeline integrity monitoring. The basis for the selection was based on some analogue experiment of comparing deflection due to structural loading and change in gradient vector due to leak.

In summary the technology solution for the crude oil theft monitoring in the Niger delta was delivered based on a proof of the hypothesis which is based on observed data using vector analysis of real-time, online pressure measurements based on post-leak data diagnostic smart operations.

This proof is based on deductive reasoning of the post-leak data diagnostic process based on smart fields operations selected technology concept.

3 LITERATURE REVIEW

3.1 Introduction

The current Oilfield reliability-based maintenance process for managing pipeline integrity is based on *plan-do-check* loop aimed at continuous improvement. The *Plan* involves the generation of integrity failure modes like the rate of corrosion. The *Do* involves surveillance activities for data acquisition like corrosion logging while the *Check* involves a comparison of the plan and the acquired surveillance data in other to advise on an improvement plan. The data acquisition process is normally based on non-destructive inspection to monitor and recalibrate rate of corrosion. The result from the acquired data is then used for remedial activity planning. Such remedial activity could involve the repair of corroded pipeline sections. Visual inspection can sometimes be used as a guide where the pipelines are not buried. The data acquisition focus is on material thickness monitoring and this is usually achieved using logging tools. The logging efforts could be external or internal. The internal logging tools could be via wireline for vertical pipes as used in oil wells. Tractor assisted logging tools, or pigs which are pumped with fluid to sweep the pipeline being investigated are used for logging in horizontal pipelines. One major disadvantage of internal pipe monitoring however is that they require flow interruptions during such data acquisition operation. The external logging on the other hand are sometimes not feasible especially where the pipelines are buried and could sometimes be awfully expensive in deep offshore pipeline inspections.

The concept of hazard and effects management process (HEMP) was introduced as a first step before delving into the details of seeking solution to the problem of oil theft. The research literature review was therefore executed in two stages.

- The first stage discusses technology solutions based on process approach and by considering strengths and weaknesses of each approach selected the most suitable approach for detailed literature review.
- A technology literature review for the selection of technology concept for the realisation of research objectives was thereafter undertaken.

3.2 Hazard and effect management process

The hazard and effects management process is a risk management process that is used to install a set of barriers to top events (incidents or accidents) and where such events have occurred uses another set of barriers to prevent escalation. HEMP is specifically tailored to a particular event after a detailed study of the process that could lead to the event's top event which is the accident itself. If we consider a car for example and consider a fatal accident as a top event, then we can consider the MOT road worthiness of the car as a barrier. We can also consider the weather, the nature of the road, the mental condition of the driver as barriers. The MOT roadworthiness would have assessed the vehicle and certified that all HSE systems in such vehicle are functional. Also, the driver is expected to be mentally alert and not under the influence of any drug such that the driver can read, obey road signs and promptly re-assess weather effect on roads in his itinerary as part of journey management plan. However, where these set of barriers fail and the vehicle is involved in life threatening accident, we depend on another set of barriers, called recovery controls, to ensure that the impacted passengers are saved. The recovery barriers would include police and ambulatory services response time, overall city accident response management, availability of rapid helicopter services and medical emergency evacuation (MEDEVAC) services to save accident victims. The description above represents hazard and effects management process

(HEMP) which is widely used in oil and gas industry and is the basis for emergency response preparedness for any process that could lead to high potential incidents.

A systemic hazard and effects management process for the concept design phase of an autonomous vessel has been documented (Valdez Banda et al., 2019). The hazard and effects management process (HEMP) for the design of the top event *bow-tie* diagram involves:

- Hazard and potential effects identification
- Risk evaluation
- Identification or installation of safety controls or barriers
- Establishment of risk reduction measures

The hazard and effect diagram for managing loss of containment during crude evacuation process can be represented as shown in figure 11.

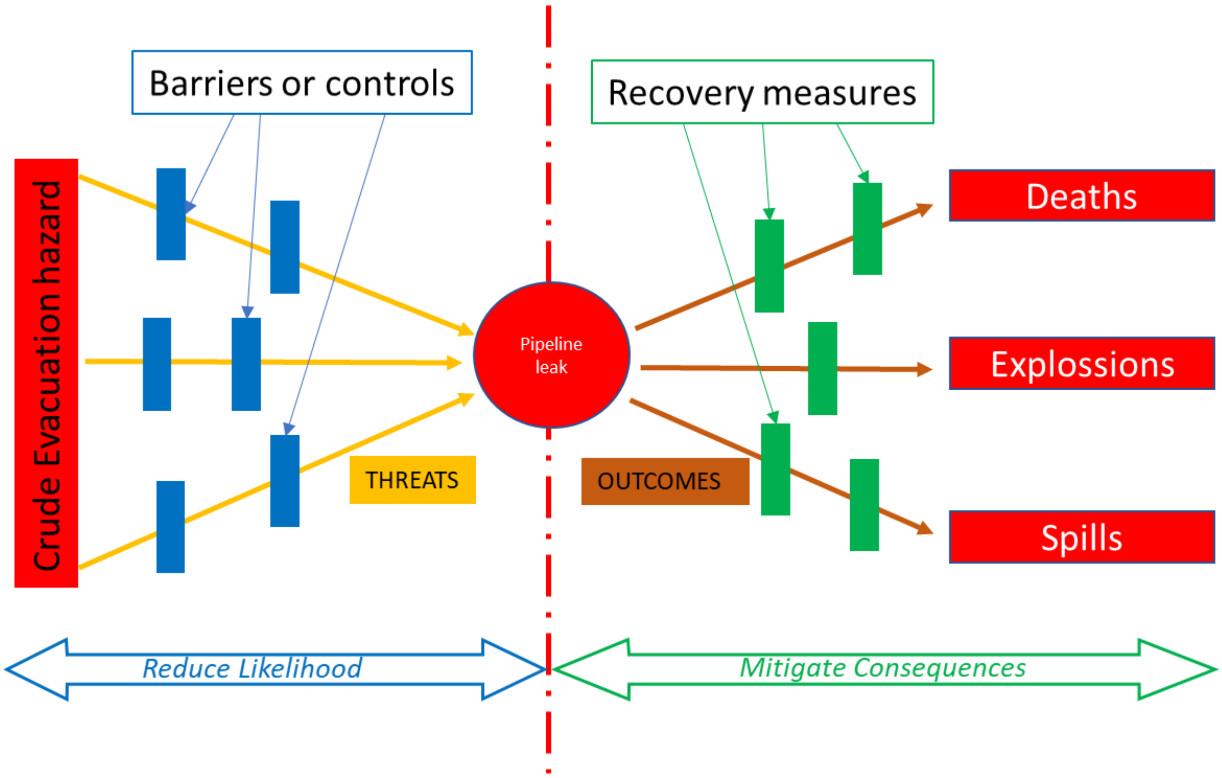

Figure 11. HEMP diagram for loss of containment during crude evacuation.

The HEMP process is a bow tie diagram that is centred around the top event. The high-risk operation and its control barriers for the prevention of the top event are placed on the left side of the top event while the potential outcomes and recovery measures are shown on the right. It should be noted that the barriers could be warning signs informing people of buried pipeline transmitting crude oil under pressure. It could also be part of the pipeline design and operations to ensure that the crude is safely contained within the pipeline. On the right-hand side of the bow tie, the recovery measures could be some early warning signs to inform the operator that some loss containments have occurred so that the crude evacuation process could be halted to reduce spill and subsequent explosions and deaths that could arise due to the spill.

The three ways of managing known risks based on the HEMP process are: 1.) reject risk, 2). transfer risk or 3.) accept and manage risk. E.g., if we imagine travelling at night and in bad weather to donate blood to an accident victim in a hospital as a risk. In this given example the potential blood donor could reject the risk by refusing to travel under the very bad weather at night. The donor can also transfer the risk by asking for the ambulatory services to come to his or her current location for the tests and collection of the blood being donated for transfusion. The third option will involve accepting the risk and taking all necessary precautions to travel at night and in the bad weather. Ismail Iqbal et al. (2021) described this hierarchical risk management approach as focus on:1.) risk elimination, 2.) risk substitution, and 3.) risk engineering controls. Some of the engineering controls, including those related to regulation and legislation in the USA are documented by Henrie et al (2016)

Applying the same HEMP risk management principles to crude oil evacuation through pipelines, the option of rejecting the risk is not acceptable. There is no other way of transporting large volumes of liquid over a long distance on a continuous basis. Also, the option of risk transfer is not possible. It is near impossible logistically to sell the crude without having a sea terminal from where ocean-going vehicles could load them. It is also impossible to build inland refineries for a few cluster of wells. So, we must accept the loss of containment risks during crude evacuation to export terminals and find ways of minimising risk due to loss of containment. It is hoped that this research will strengthen the crude evacuation HEMP process by adding either a control barrier or a recovery barrier in the management of loss of containment during crude evacuation process.

Accident is a product of likelihood of the occurrence of an act, like crude loss of containment during evacuation, and impact of the occurrence of such act (spill, explosion and deaths). The fact that a particular incident has a low likelihood of occurrence does not imply that it could not happen and hence HEMP ensures that suitable barriers are installed to reduce the likelihood of any high potential accident. The control barriers in the HEMP diagram could be in any form. Using the example of vehicle accident HEMP described above, such barriers could be physical e.g., HSE critical systems in the vehicle but it could also be regulatory e.g., thou shalt not drive under the influence of alcohol. Other regulatory barriers include installation of road signages specifying direction and speed limits. Similarly, loss of containment barriers for crude evacuation process could be regulatory or physical. Regulatory controls would include design and approval processes for authorization of pipeline installation and approvals. Physical barriers would include the materials type, thickness used for the pipeline installation, monitoring equipment used for integrity monitoring of the pipeline during operations etc. On the other side of the HEMP bow tie, the recovery measures that could be installed could include timely detection of leak such that the pumping operations can be timely stopped to reduce the likelihood of deaths due to explosion. Other recovery measures would include the organisations emergency response (including MEDEVAC) preparedness. There are also operational fines and punishments to organisations for leaks due to carelessness, indolence, and dereliction of duties, among other regulatory controls.

3.3 Technology preselection review

A leak detection taxonomy from Pipeline Leak Detection Handbook is presented in figure 12 (Henrie, Morgan; Carpenter, Philip; Nicholas, 2016). Henri et al (2017) has grouped pipeline detection technologies into two broad themes: Incidental observation and design-based leak detection systems. The design-based leak detection system was further regrouped as those based on external sensors and those based on internal sensors.

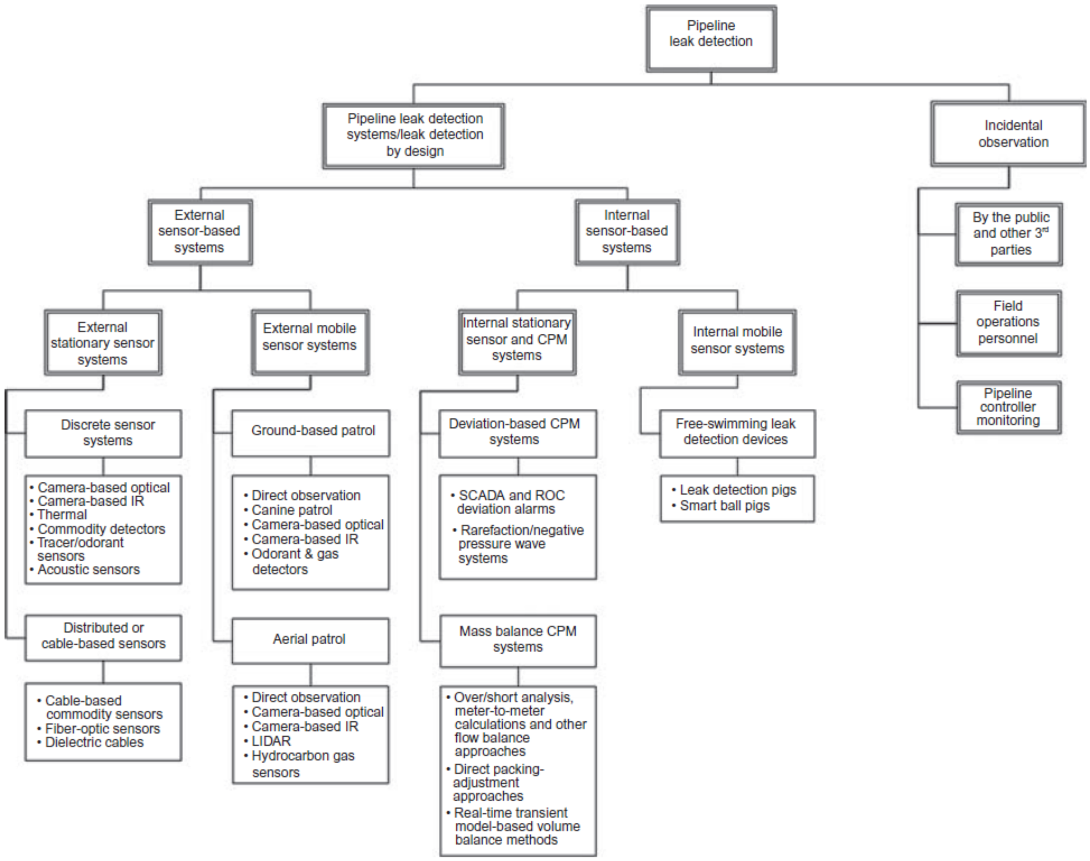

Figure 12. Leak detection taxonomy (Henrie et al, 2017)

Based on the pipeline leak detection handbook and for the purpose of this research, the leak detection systems can be grouped as :

- Incidental observation
- External sensor-based systems
- Internal sensor-based systems

3.3.1 *Incidental Observation*

Observation is one of the oldest process applied in leak detection. Whether it is an accidental discovery of oil seeping out of a farmland, oil sheens on local streams, contaminated potable water table, smell of oil vapours in the air we breathe or abnormal pressure changes at operations control centre, this incidental observation gives an indication of leak or theft. Also, the inability to receive all that is pumped is also an indication of leak or crude oil theft. Usually, any incidental leak observation is reported to local authorities or the operator for detailed investigation, clean up and repairs. Part of the recovery measure in this case would be to stop the pumping operations, cordon off impacted areas, provide emergency water and food to the local communities while the remediation process is ongoing. It should be noted that in most cases such leaks could have gone on for a very long time before being detected. In some cases, e.g., seepage to a farmland, the point of detection could be used to detect the source of leak while in other cases e.g., contaminated water from shallow potable reservoirs could be a nightmare as such shallow potable water reservoir may be laterally extensive. This approach, though not reliable as the only source of leak detection has a major shortcoming that the leak can go one for a long time before being detected and is incapable of detecting crude theft as crude theft most times does not lead to loss of containment to the surrounding.

3.3.2 *External sensor-based systems*

The use of soldiers, dogs, helicopter overflies or satellite images for surveillance of the pipeline ROW are geared towards investigating leak source using optical, thermal, infra-red, acoustic, dyes and tracer equipment for leak surveillance. These operations monitor: air quality for hydrocarbon content; the location of thieves; oil sheens on farmlands or on open water surfaces and, can be used to determine leak due to loss of containment from any evacuation pipeline. It should be noted that crude theft most times do not lead to loss of containment because rogue conduits are attached to redirect some of the crude flow to stationed rogue vehicles. This therefore means that even though the control room observers are able to determine that some crude theft is ongoing, such activities will not be observed through air, soil or water sampling or observation. The helicopter overflies are aimed at locating the operations of the crude oil theft by seeking out freshly excavated soil locations in dense vegetations. Another downside to the use of external based sensor systems to monitor crude oil pipeline theft is that the thieves are observant and would employ suitable means to avoid being caught. Such means could involve hot tapping at night or during poor weather when it is obvious that helicopter overflies cannot take place. Also, even when the observation process, especially at operations control centre, is able to detect some crude theft it will not be able to exactly point where the theft is ongoing, and this limits the application of the observation process for crude theft point prediction.

Some of the external sensor systems that could be very useful in this research, as documented by Henrie et al (2017) include fibre-based commodity sensors, fibre optic sensors and dielectric cable. This research is not about leaks in commodity pipeline transportation, so the use of commodity specific sensors was not considered. Dielectric sensor technology is a post leak environmental monitoring technique for measuring the thickness of layered films and hence is not considered in this research which aims at leak prediction or prognostication. The only suitable technologies from these set of external based sensor systems are acoustics and fibre optic sensors.

3.3.3 *Internal sensor-based systems*

Internal sensor-based leak detection systems can be based on deviation trending and mass balance. Also, the use of pigs and smart pigs can be used to detect leak point as documented by Henrie et al (2017). These internal leak systems are most relevant to this research. The use of pigs and smart pigs will be discounted because they require production interruption and hence outside the operational domain of pipeline operations. The use of free-swimming detection systems which can also be described as micro robots were considered useful but still at its developmental infancy.

3.3.4 *Summary of technology process review*

Based on the preselection leak detection technology review we can progress this research through a detailed literature review of internal sensor-based systems and some external based sensor systems. Most of the leak detection systems based on external sensors are not applicable because a leak must have happened before the can be useful. In some of the internal systems, a leak may also have happened, but the operational design of such leak detection system is to reduce the response time between the leak and the activation of emergency actions to stop operations and arrest loss of containment escalation.

The available technology for leak and intrusion detection could, based on the foregoing, be hardware based or software based or a combination of both. The hardware methods require physical measurements which could be using acoustic, optical, ultrasonic, or some form of environmental monitoring like soil, surface water, or air quality sampling. Software based methods involve the use of algorithms to continuously monitor the state or rate of change in pressure, temperature, flow rate in a closed system (Murvay & Silea 2012). The trends of such parameters and deviations therefrom could be used to predict leak and this could be achieved without the requirement for flow interruption.

Prior to the onset of regular pipeline vandalism in Nigeria, it was thought that every spill is related to operation (corrosion, pressure mismatch or some system upset). However, the review results following every spill showed that most of the spills since 2000 were due to vandalism. This operating environment motivated the international operating companies (IOCs) to collaborate with Nigerian regulators and host communities to set up a joint investigation team (JIT) after every spill for incident reviews. The team agreed among other things, that a way of preventing vandals from benefiting from crime would be to ensure that post spill compensation will no longer be paid to any host community if the JIT review reveals that any spill was because of vandalism. This temporarily stemmed down the rising trend in spills due to vandalism until the vandals discovered that they could make more money siphoning and selling the crude rather than receiving stipends as compensation due to loss of farming or fishing revenue from spills.

Environmental monitoring methods, or external sensor-based leak detection systems, are outside the scope of this research because a loss of containment need to have occurred for these methods to be effective. The technologies based on mass balance, real time transient modelling, acoustics, pressure point analysis, statistics or digital signal processing, optical cable sensor, and ultrasonic flow metering were assessed as attractive. Some of these technologies could be combined e.g., corrosion monitoring could be based on statistical sampling for update of existing integrity models. Also, mass balance, real time transient modelling, and pressure point analysis could be combined into some form of smart operations monitoring technology. Pigging, which is a standard oil pipe sweeping operation, is the process of pumping some specially designed cylinders that are called *pigs*, whose external diameters are slightly less than the internal diameter of the pipes they are designed to sweep. Any pipeline designed for pigging operation must have a pig launching pad and a pig retrieval pad and these pads demand some production interruption during pig launching or retrieval, respectively. Some delivery lines are designed for pigging while most trunklines are not. Smart pigs have multi-finger callipers for monitoring the respective pipeline thickness at respective pipeline sections during the pigging process. The use of pigging technology for trunkline integrity monitoring will not be progressed further because such technology requires production interruption which is not desirable in major evacuation trunklines.

A detailed technology literature review of some of the more promising technologies for pipeline integrity monitoring is presented below.

3.4 Technology literature review

3.4.1 *Fiscal reconciliation*

Crude oil is measured at different stages of its flow: at wellheads, manifolds, flow stations, central processing facilities (CPF), up to central tank farms (CTF) or oil terminals where they are sold or exported. Some differences, between the total crude evacuated from producing wells and total receipts at the terminal, are usually noted during the transport process from the wellhead to the CTF. These differences are either due to different meter accuracies, shrinkage losses due to temperature variations, liberation of dissolved gasses, or due to leaks. The differences due to different meter accuracies, shrinkage losses due to temperature variations, liberation of dissolved gasses are usually minor and at most could account for a maximum of about five (5) percentage variation. As long as these differences are within this 5% pre-set limit the difference can be acknowledged as an acceptable reconciliation loss but if the difference is large it could be due to an abnormal causes like pipeline leakage or pilferage that needs to be attended immediately (Chebiyyam, 2010).

One of the early signals that some crude theft is ongoing is a comparison of the fiscal reconciliation of the total fluid received at the export terminal to the summation of all the crude pumped into the pipeline export route. This reconciliation process could be single or multi-staged, but most operators choose two stage reconciliation process. The single stage reconciliation process involves the comparison of the total well head tests and the total oil receipts at the tank farm. A two-stage reconciliation involves a 1st stage reconciliation between the oil terminal or tank farm and the several flow stations supplying to the tank farm. The 2nd stage reconciliation uses the single stage RF to back calculate what the intermediate stage reconciliation would be. This process could yield the sections of the pipeline network that could be investigated due to their low RFs. There could be additional reconciliation stages, but some form of measurement is needed for each additional staging in the reconciliation process. Example, there could be an intermediate reconciliation between the flowstations and the terminal at major manifolds. This would mean that we must have a means of measuring what flows through those major manifolds. Fluid reconciliation factors would usually get close to 1.0 without leaks or crude theft but drifts away from 1.0 depending on the rate of leak or theft. A reconciliation factor of 0.95 is acceptable as some shrinkage losses are expected as the crude is pumped for export. However, an RF of 0.75 implies that one out of every four barrels produced is stolen. Helicopter overflies are usually undertaken by operators to check for oil spills or recent soil excavations along the pipeline ROW once consistent low RFs are recorded.

A major disadvantage of using fiscal reconciliation surveillance technology is that it is a post-mortem approach. Fiscal reconciliation is also an end month activity as required by standard oilfield practice and regulation hence the oil theft could have gone on for a long time before the end month reconciliation time. Also, any reliance on fiscal reconciliation for leak or intrusion monitoring would therefore require huge operational upgrade as additional process instruments may have to be installed. Multistage reconciliation could be employed if we need to know the area of leak position to some coarse accuracy, but this will increase the system operating costs and while the use of such technology could coarsely indicate an area of potential leak or crude theft it is unable to point the exact position within that area.

3.4.2 *Corrosion monitoring*

Fatigue stress initiation in pipelines could be attributed to corrosion, manufacturing defects or operational effects whose growth could be enhanced by cyclic loading caused by the operating pressure of the transported fluids (Ossai et al. 2015; Shabarchin & Tesfamariam 2016). All pipeline structures are subjected to varying and fluctuating pressure stresses and are exposed to harmful environments externally and corrosive environment internally during their service life. The fluid composition of the hydrocarbon being evacuated, especially the presence of carbon dioxide, could lead to internal corrosion. To counter the effects of this operating environment special consideration is usually made during the specification of pipe thickness, pipe physical properties, and the martensitic treatment for pipeline steel.

Corrosion monitoring involves the use of a material scientific data to predict the pipeline material thickness loss per unit time in any given service environment. These performance data, for the respective service environment, are based on manufacturers experiments. Once a corrosion model has been made, the operational integrity monitoring would involve regular data acquisition for continuous update of created model for the prediction of pipeline failure. The frequency of data acquisition depends on service conditions and could be changed with time to manage assessed risks. Within the E&P business, each operating company use their proprietary software to predict corrosion rates in terms of wall thickness reduction per unit time and use such data to determine design safety factors during pipeline design, installation, and operation. Regular operations monitoring is undertaken by such companies to determine actual corrosion rates during operation.

Hence, based on design and operations PM surveillance programme, the state of most pipelines could be said to be known. However, one of the major hindrances to pipeline integrity monitoring using PM surveillance approach is accessibility to these pipelines for corrosion rate measurements. This lack of access could be because of urban encroachment, obstructions, or legacy issues that make the host communities hostile and hence prevent operators from having required access for surveillance operations.

Despite these detailed understanding of corrosion mechanisms and improved corrosion monitoring techniques, industry reports still show that internal corrosion still plays a significant role in pipeline failures. For example, according to an Alberta Energy Regulator report (AER, 2013), from 1990 to 2012, more than 9000 failures occurred due to internal corrosion, and these failures accounts for 54.8% of all spills in that area. It should be noted that leaks due to corrosion happen, not necessarily because of the corrosion, which is always there, but due to lack of proper assessment of the extent of corrosion or lack of adequate mitigation actions based on assessed corrosion risk. Typical mitigation actions could include reducing the operating pressure of such pipeline so that they can still operate within their designed safety factors based on the estimated wall thickness reduction. Pipeline loss of containment spills will therefore not occur if pipelines are continuously de-rated based on measured or estimated thickness reduction due to corrosion or decommissioned when the de-rated pressure are no longer enough for sustained crude evacuation.

As a result of the foregoing discussion, which is based on over five decades of oilfield practice in the Niger delta, it could be said that the current use of preventive maintenance (PM) and corrective maintenance (CM) actions are effective though not sufficient for pipeline integrity monitoring. What would be needed therefore in this technology area is due diligence in data acquisition for continuous corrosion monitoring update. The results from such model update could be used to generate heat maps for planning of CM actions which can include pipe cladding, pipeline sectional replacement, or for the determination of abandonment conditions for the entire pipeline. One other option for the use of corrosion monitoring could be in the design of some early warning systems prior to leak. Such an early warning system could be based on the model generated heat map or could involve the use of probes, as shown in figure 13. The probe in figure 13 (ALABAMA SPECIALTY PRODUCTS, 2020) will be made with the same material as the pipeline and properly sized to the pipe material thickness such that they would give signals when some pre-set material thickness, say 50%, is lost. This technology is what is currently used for measuring sand erosion in oil and gas transport pipelines and could be used to monitor pipeline material deterioration of any type. This approach could be used as a guide for pipeline de-rating prior to its replacement.

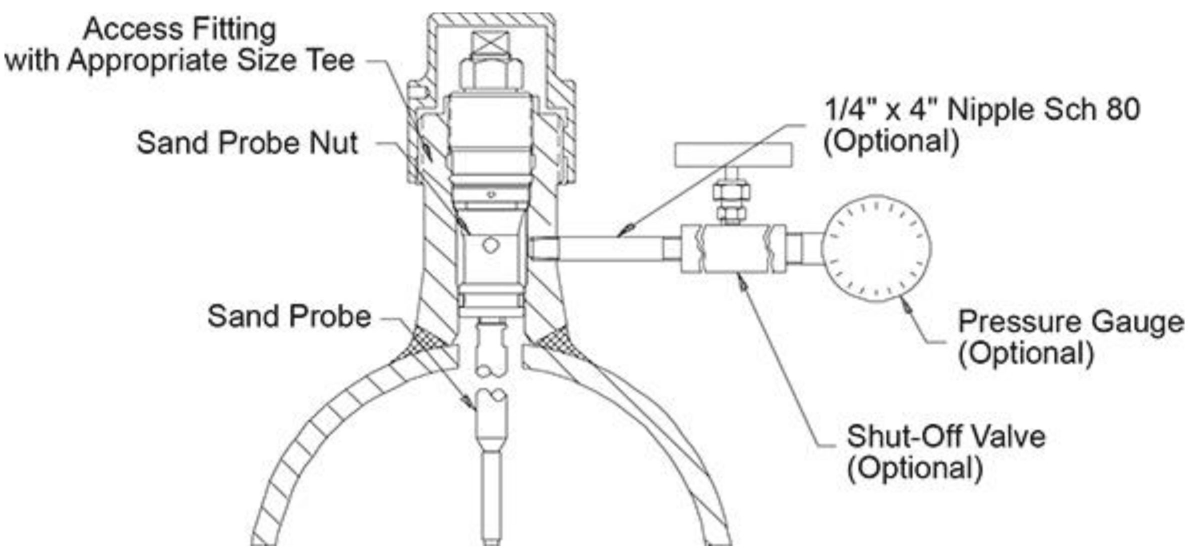

Figure 13. Corrosion monitoring probe schematics (Alabama Specialty Products, 2020)

Figure 13 shows how the use of probes can be installed as part of the pipeline system. The probe is in the form of a tube and made with the same material but sized to measure a thickness reduction that is critical to the operation of the given pipeline. During the crude evacuation process, the installed probe would corrode with the pipeline but since it has a smaller thickness it would wear out faster than the enclosing pipeline. Once a wear threshold is attained a wear creates a hole in the probe and this will be sensed and measured on the attached pressure gauge and this would signal a designed thickness reduction due to internal erosion or corrosion.

This combined use of PM and CM for corrosion monitoring was an effective process for pipeline integrity monitoring until the onset of pipeline vandalism for crude oil theft. The PM and CM process approach still supports a statistical approach for reliability prediction but could be upgraded to some level of smartness using heat maps or sacrificial probes, but these would come with additional capital and operating costs. The use of probes needs further research to see how it could be accommodated in the trunkline design changes. The use of corrosion monitoring can be used to create a Pre-leak data prognostic method as discussed on page 118 but a major disadvantage for corrosion monitoring is that, since it is based on statistics, it would not be able to detect the exact point of leak and it is also not designed to measure the leak rate.

3.4.3 *Hydraulic flow simulation*

Hydraulic flow simulation is an attempt at replicating actual hydraulic flow process from one point to the other in a closed system. The hydrocarbons flow from the subsurface reservoir to the wellbore and then from the wellbore to the wellhead. Then from the wellhead to the gathering stations where the hydrocarbons are stabilized after separation into gas and liquid or sometimes into gas, oil, and water. The stabilized crude from the flowstation is then pumped to the export terminal where further stabilization is executed at holding tanks to meet export quality prior to sales. The wells in onshore operations could be spread over acres of land and the crude are required to flow naturally or artificially assisted to some considerable distances to the gathering station where some separation is done, and stabilized crude pumped to the export terminal that could be several tens of kilometres away. Figure 14 (Corken, n.d.) show a schematic cartoon of a typical onshore network from reservoirs up to the gathering stations that could be simulated to get solutions that can be continuously monitored for production optimization and remedial activity planning. It should be noted that some wells are free flowing and so are described as natural producers while others that produce from depleted reservoirs are incapable of sustaining natural production and hence are assisted manually or electrically. These later categories are classified as assisted production or artificially lifted wells. Bean pumped wells as shown in figure 14 and jet pumps are non-naturally producing wells. Other form of vertical lift assistance includes gas lifting and several forms of electrical pumping (electrical submersible pumps, screw pumps etc.).

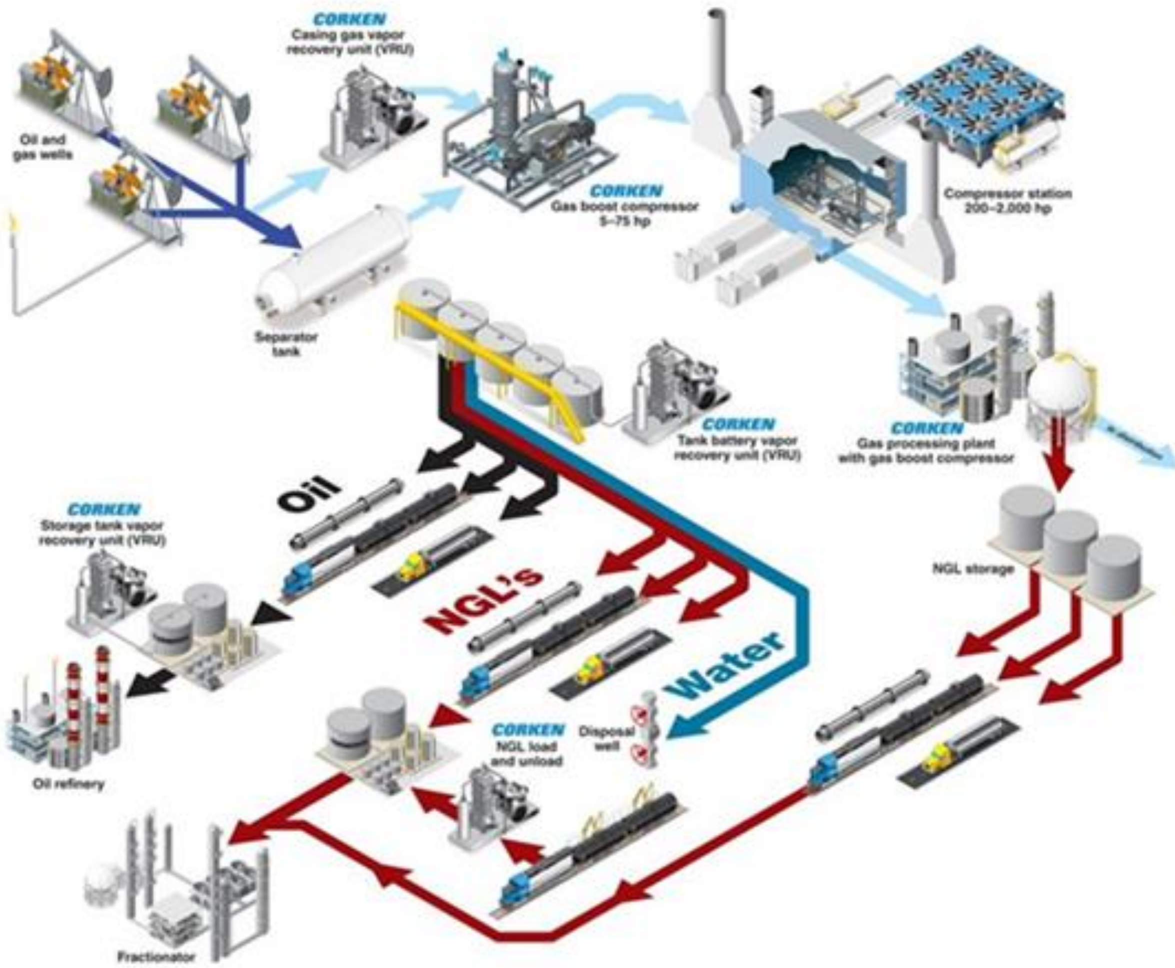

Figure 14. A typical onshore network from reservoirs up to the gathering stations (Corken, n.d.)

The PETEX IPM[3] suite is one of the readily available hydraulic flow simulators and is widely used for hydraulic simulation in the oil and gas industry. Petroleum engineers use this workflow as part of their routine operations. Some of the results from this workflow using IPM suite in the industry to demonstrate the software capability in several operating units around the world have been published (Layer et al. 2011; Montero & Nwankwo. 2010; Omole et al. 2011; Pothapragada et al.

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[3] PETEX IPM is a flow modelling software from Petroleum Experts. https://www.petex.com/products/ipm-suite/

2012). These reviews show that the IPM tool can be used to accurately model hydraulic flow from reservoir to the flow stations and can be used to forecast oil and gas productions from such hydraulic systems. Figure 15, which is typical of a Niger delta Operations, shows a modelled network generated for twenty-six reservoirs, sixty-nine wells, and two flow stations. This model is presented to show how the research objective of monitoring oil leak or pipeline vandalism could be realized through technology extension of the IPM proven capability for modelling fluid flow from wells up to the flow station. If we can model flow from wells to flow stations, then we could also model fluid flow from flow stations to export terminals at the same level of accuracy.

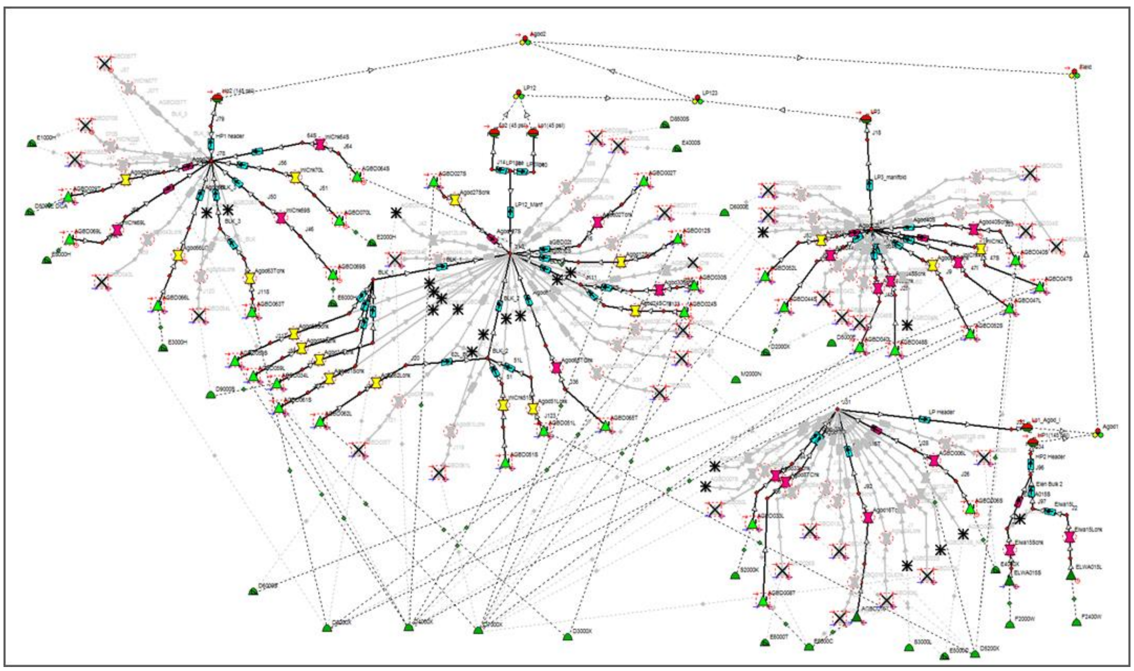


Figure 15. Simulated hydrocarbon flow network

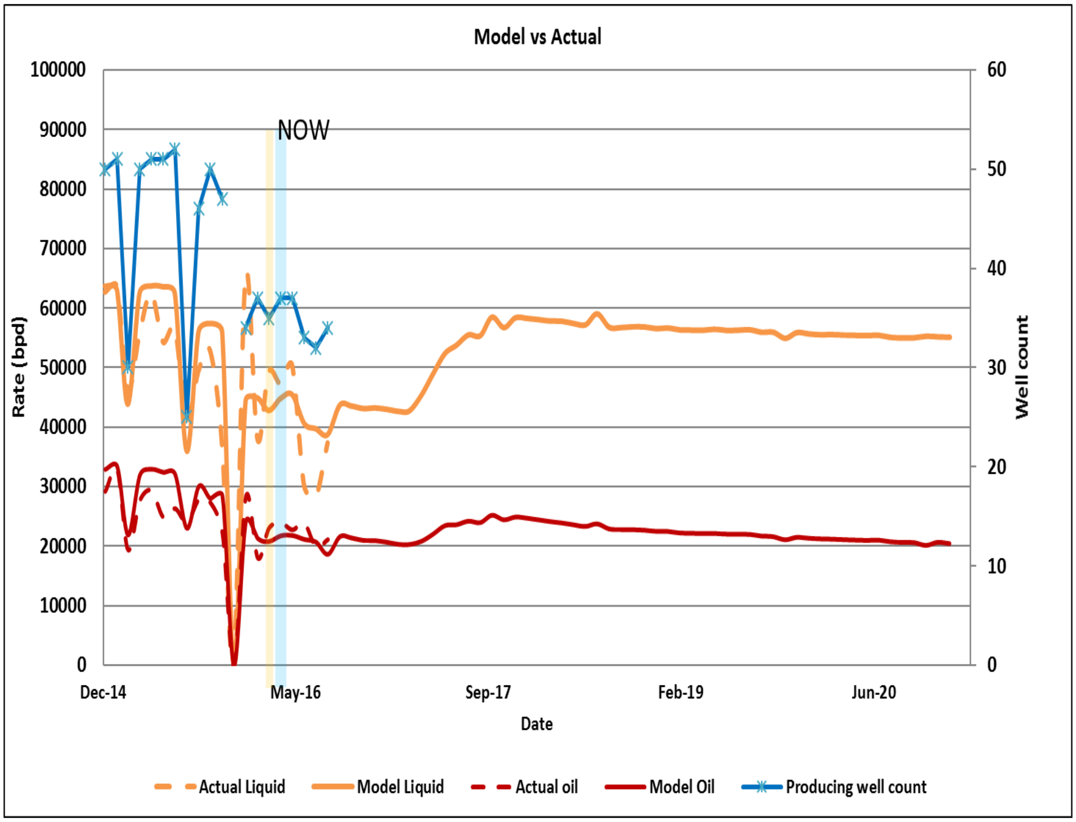


Figure 16. Matched performance and forecast from simulated flow network.

Figure 15 is a simulated hydrocarbon flow schematic from reservoirs through wells up to two gathering stations. It should be noted that the flow described here is a natural flow through a 4-inch flowline, but the concept is applicable to stabilized fluid pumping through trunklines. Figure 16 shows the matched performance from December 2014 to September 2016 from the created IPSM model as well as forecast production from October 2016 to December 2020. The simulated result compares reasonably well with actual production. The observed gap between the simulation result and the actual production is noted but still acceptable because the production data used in this analysis is already reconciled and hence has already been affected by some production losses, described in section 3.4.1, through the larger production network for the operating unit. The use of hydrocarbon flow simulator to forecast production could be designed and used to monitor conformance to predicted performance and hence determine leak points and rate of crude that are either leaking or being siphoned by oil thieves.

What is required in support of this leak detection and quantification research process (*Hypothesis – Data observation – Confirmation of Hypothesis*) as documented in Research process page 50 therefore is flow simulation and forecasting of the volumes, pressures and temperatures that would be flowing through the respective sections of any evacuation pipeline for comparison with actual performance. The downside to this modelling approach, based on current practice, is that measured data are only recorded at only three distinct points: at well test points, the flow station export points, and the export terminal. This therefore means that if there are leaks, we would know that leaks have occurred due to fiscal reconciliation, but the exact point of the leak may not be known except with increased monitoring points. A lot of monitoring points would therefore be needed if we must reduce the uncertainty associated with the actual leak or theft point prediction using this technology.

3.4.4 *Smart fields operation*

Smart fields operation is an artificial intelligence workflow that uses instrument sensing, computer modelling or simulation, and SCADA to partially perform human tasks aimed at reducing the decision cycle time for data-based decisions as well as managing production data uncertainties. The most common data needed for smart field operations are pressures, temperatures, and volume flow rates. These data are needed for complete description of hydrocarbon recovery and throughput from the reservoir to the export terminal. Starting from the wells, through the flowstation, up to the export terminals, sensing devices could be installed as part of smart operations to monitor pressures, temperatures, and flow rates. Figure 17 shows a typical smart well concept for producing and commingling three reservoirs within a well. Specifically, the *Smart* completion components include control lines for sending open and close signals to interval control valves (ICVs), electric lines for recording pressures and temperatures from installed gauges in addition to all the other safety critical equipment like production packers for hydrocarbon process containment. In this case, which was a project undertaken for an operator in the Niger delta, the pressure gauges were designed to measure both the internal pressure of the fluid being produced as well as the external pressure of the surrounding production annulus as part of the well integrity monitoring process. Readings from these sensors are remotely monitored and signals could also be sent to this well which is about 11000 ftss for production system optimization. Such optimization could involve closure of watered out or gassed out intervals for increased production of valuable crude oil. It could also include opening the chokes from each contributing reservoir for production optimization. An inbuilt advantage of such smart well, for which a digital twin can be created based on Hydraulic flow simulation, would eliminate expensive rig operation for well repairs for accessing new zones.

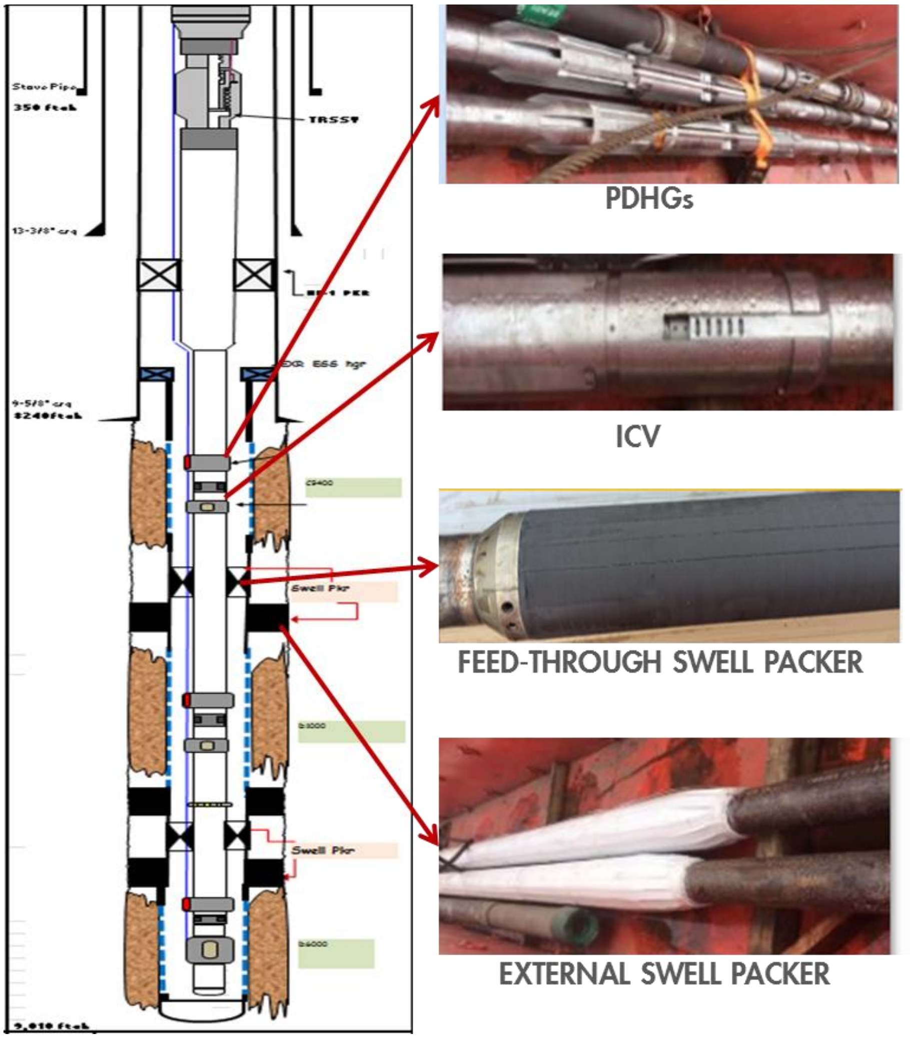


Figure 17. Smart well design and components

The smart field operations for data acquisition, transfer, monitoring, simulation and interpretation from the reservoirs, wells, flowstations, pipeline manifolds up to the export terminals have been studied and documented (Goel et al. 2013; Cullick & Sukkestad 2010; Montero & Nwankwo 2010; Omole et al. 2011). An improved process for the allocation of hydrocarbon throughput from different flow units within the reservoir using the smart workflow based on Hydraulic flow simulation have also been studied and documented (Edih, M., Nnanna, E., Nwankwo, C. 2016) and (Mabel Pei Chuen et al., 2017). A similar process improvement could be crafted for trunklines and used to address the research hypothesis which has been crafted as:

If we have a way of continuously measuring the steady state conditions at regular intervals (say 5km or 10km) on a given pipeline during operation, then we could, through deviations trending from the steady state operation, determine the point of leak or crude oil theft and quantify leak rate or theft.

If Edih et al (2016) and Mable et al (2017) have demonstrated that, through the use of smart operations modelling, the flow contributions from the different sections of a well could be determined accurately, then through the same workflow we could determine the leak points and leak rate from the respective sections of any given trunkline through deductive reasoning as documented on Research process page 50. The smart field flow configuration could be broken into convenient nodes like the reservoir node, the wellhead node, the flowstation node etc. such that real-time data from these nodes could be matched with modelled data to determine if there is a deviation between the model prediction and actual performance. Using a properly calibrated model there would be little deviation between the model prediction and actual measurements from the installed gauges. This therefore means that any major deviation between a properly calibrated model prediction and actual measurements will be attributable to leak or theft. As a result of the foregoing, the smart field operation concept could be used to install more measurement devices on trunklines such that we can record data that can be used to compare the flow through various sections of the trunk line to determine if some of the crude being pumped are leaking or stolen.

This use of smart operations capability could be a particularly good fit to the research objective of leak or theft points determination and leak rate (or theft rate) estimation. Smart operations technology could be used as a standalone technology or could be combined with Hydraulic flow simulation to accurately determine the rate of leak using digital twinning as documented in section 9.6.2 on Digital Twining in pipeline fluid evacuation process page 199. The downside to this technology is that due to operations design limitations wet flow measurements for volume flow rate is still a challenge in oil trunklines. There are also challenges on how to deploy suggested additional pressure measurement points without compromising the installed pipeline integrity as every pressure monitoring point is a potential leak point.

3.4.5 *Fibre optic sensing*

A fiber optic sensor uses optical fiber either as the sensing element, or as a means of relaying signals from a remote sensor to the electronics that process the signals. Depending on the application, fiber optics may be used because of its small size, or because no electrical power is needed at the remote location, or because many sensors can be multiplexed along the length of a fiber by using light wavelength shift for each sensor, or by sensing the time delay as light passes along the fiber through each sensor (Wikipedia, 2017). Some of the several applications of fibre optic sensing technologies include the use of fibre gratings, fibre optic cables and distributed temperature sensing technologies. The use of fibre Brag grating (FBG) and fibre optic sensors for monitoring, diagnosis and control in civil structures as well as in pipeline leak detection has been studied and documented (Ahadi & Bakhtiar, 2010; Davis & Brockhurst, 2015; Ko & Ni, 2005; H.-N. Li et al., 2004; Majumder et al., 2008; Murvay & Silea, 2012; Tanimola & Hill, 2009; Yan & Chyan, 2010). In particular the application of fibre optic leak detection and third party intruder detection methods have been successfully demonstrated to provide non-intrusive digital pipeline monitoring by acting as an early warning system, allowing operators to act swiftly in the event of a pipeline leakage or intrusion into a plant area or leakage into the environment (Davis & Brockhurst, 2015; Murvay & Silea, 2012; Tanimola & Hill, 2009).

The use of fibre optic for pipeline leak detection involves running and strapping the fibre optic cable along the full length of the pipeline for sensing the external temperature of the pipeline being investigated. The principle for leak detection using distributed temperature sensors (DTS), external to the pipe being investigated is that the thermal signature of the product that is being carried in the pipeline (gas, LNG, oil, water, ethylene, ammonia) will be significantly different from that of the environment surrounding the pipeline (Kim & Lee, 2009). Therefore, any breach in the pipe work will cause a release of fluid from the pipeline into the atmosphere which will be noticed by the sensors because of temperature difference. This technology could also be applied in subsea pipelines as the distributed temperature sensor is able to record subtle temperature changes due to fluid release because of its sensitivity. Unfortunately, because this technology is installed external to the pipeline it is not possible to estimate the rate of leak even if the leak point is accurately identified.

Fibre optics also has a very wide internal usage for pipeline investigation, especially in oil and gas well completion. They are installed as part of the well completion, especially in horizontal wells and used to show the sections of the horizontal wells that contribute to inflow. They could also be used, for horizontal wells to show which sections of the horizontal wells that are contributing to water production instead of oil and this knowledge are useful in remedial water shut off operations planning. The sections of the well flowing oil will display a higher temperature while the sections flowing water would be cooled down due to the contrasting specific heat capacities between oil and water. Within the Well, fibre optics has also been used to monitor wellbore integrity through continuous temperature logging to determine temperature difference between the flow conduit and its annulus.

Notwithstanding these huge potentials, a limiting weakness to this technology is that it is not tamperproof when used outside a confined space like the pipeline. Even though a severed fibre optic line could trigger an alarm, when severed, it is usually difficult for the operators to know the exact point of discontinuity especially if deployed in the monitoring of a long pipeline. Some of the pipeline vandals in the Niger delta are technically experienced professionals or employ the services of such professionals as documented in Research motivation. This means that the vandals could disable fibres if installed exterior to the trunklines. Another downside to this technology is that it is expensive, difficult to diagnose problems, and sometime exceedingly difficult to repair. Even within a secure subsurface environment, attempts to re-light these fibres when they fail in the past have proved abortive and these could lead to huge cost and value erosion. All these disadvantages make the use of this technology impractical at monitoring leak point in an open environment.

3.4.6 *Frequency response function modelling*

One property of steel pipes and rigid structures especially those made with high carbon steel is that, within their elastic limit, they are capable of springing back to their original state after perturbation. The frequency response function (FRF) or dynamic response function (DRF) which is a measure of the ratio of the output to the input signal for a given system has been used for the identification of system characteristics in engineering. The DRF of a system response, at any load, can be described by the ratio of amplitude of output to input function (F. Haghighat and D.M. Sander, 1987).

Any continuously varying force (tension, compression, and torsion) on any steel material will generate responses that could be used to calculate a DRF. Internal pressure on pipes could also be monitored and used to generate a DRF. A DRF example based on sea wave force effects on a shallow offshore platform was studied and modelled in ABAQUS[4] to demonstrate this concept and how it could be used to predict structural failure (Nwankwo, 2013). The ABAQUS finite element analysis (FEA) suite was used to design an offshore structure for a 30m water depth as shown in figure 18. Using some designed wave parameters, the wave forces estimated using the Morrison equation was used to model the effect of the wave forces on the designed structure. The DRF for each structural member were calculated as a ratio the maximum dynamic stress to that of the corresponding static load. Figure 19 shows the calculated DRF of on this designed structure for various angular frequencies and time. To verify the effect of structural failure on calculated DRF, a pair of the bottom braces of the designed structure was removed to simulate structural damage. Figure 20 shows how the DRF would be if one of a pair of the bottom braces fails as simulated.

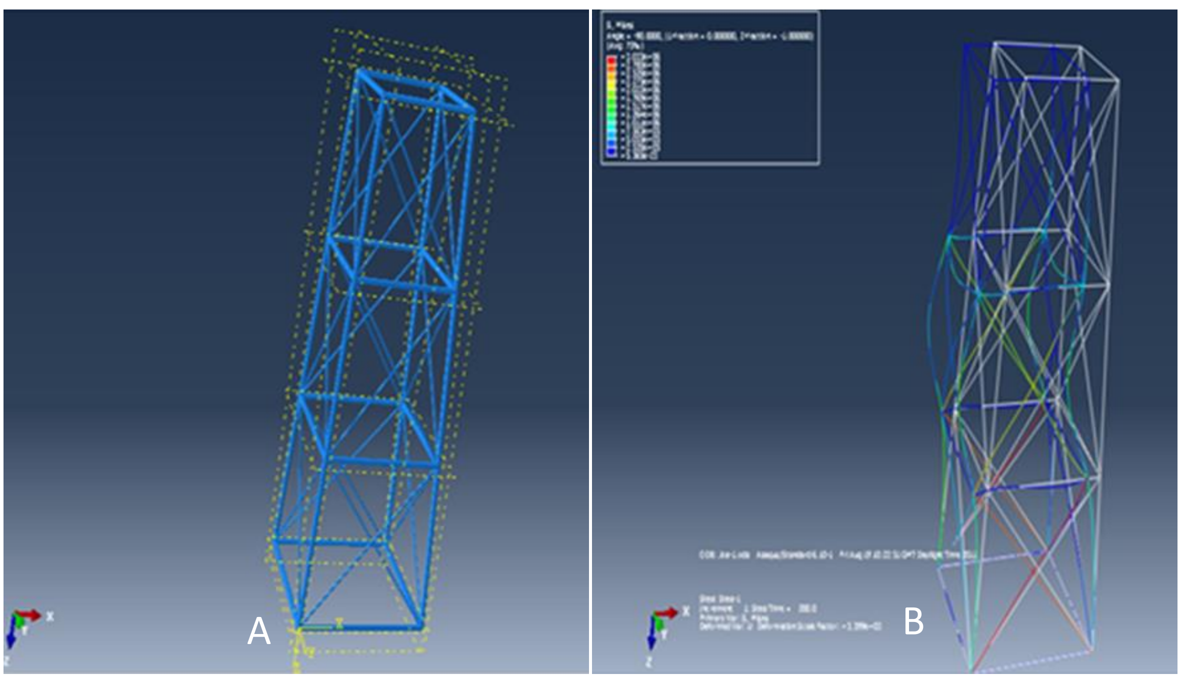


Figure 18. ABAQUS simulated offshore structure and its response to water wave (Nwankwo, C., 2013).

[4] ABAQUS is a software suite for finite element analysis and computer-aided engineering, originally released in 1978. Available at: https://www.3ds.com/products-services/simulia/

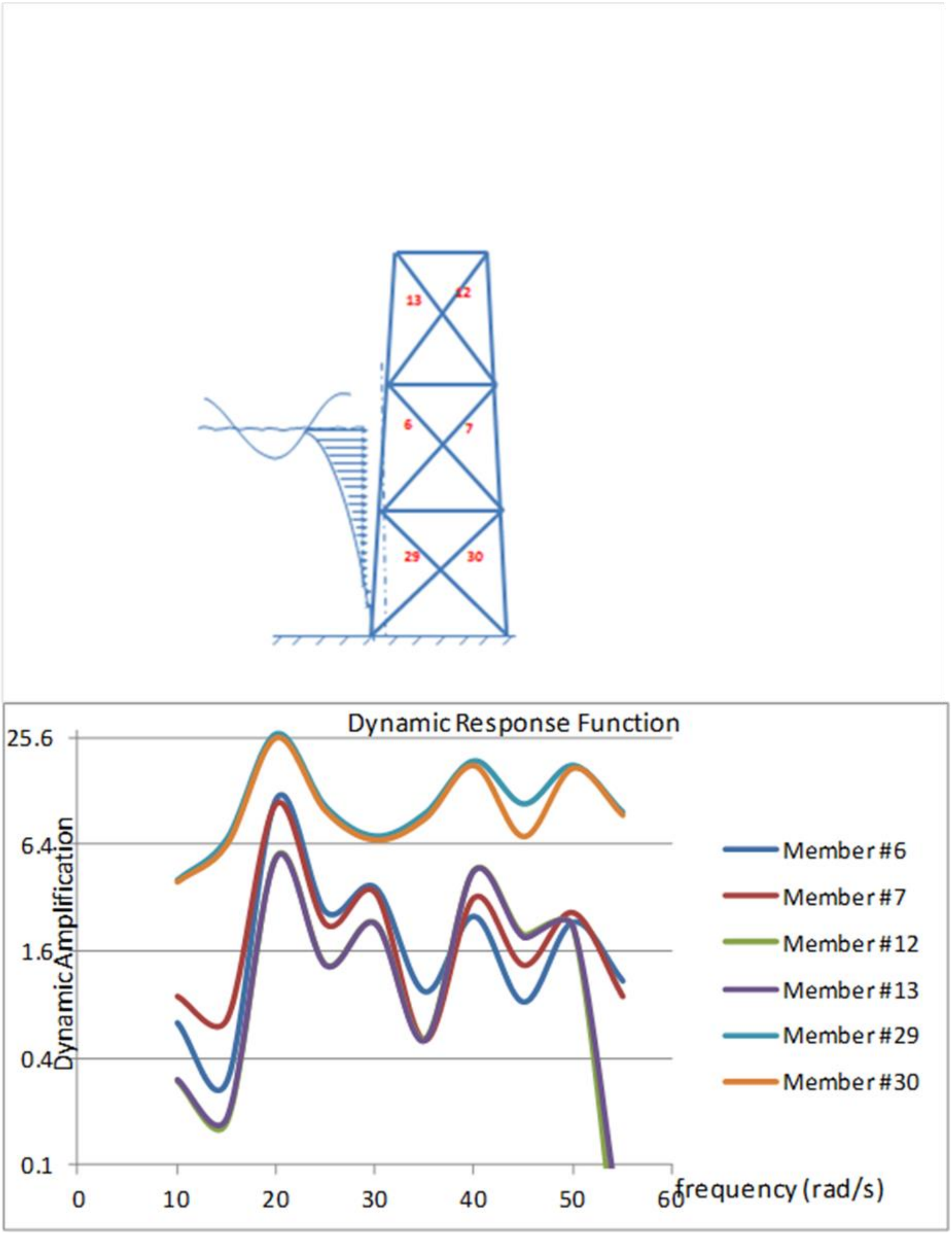


Figure 19. DRF of simulated offshore structure (Nwankwo, C., 2013)

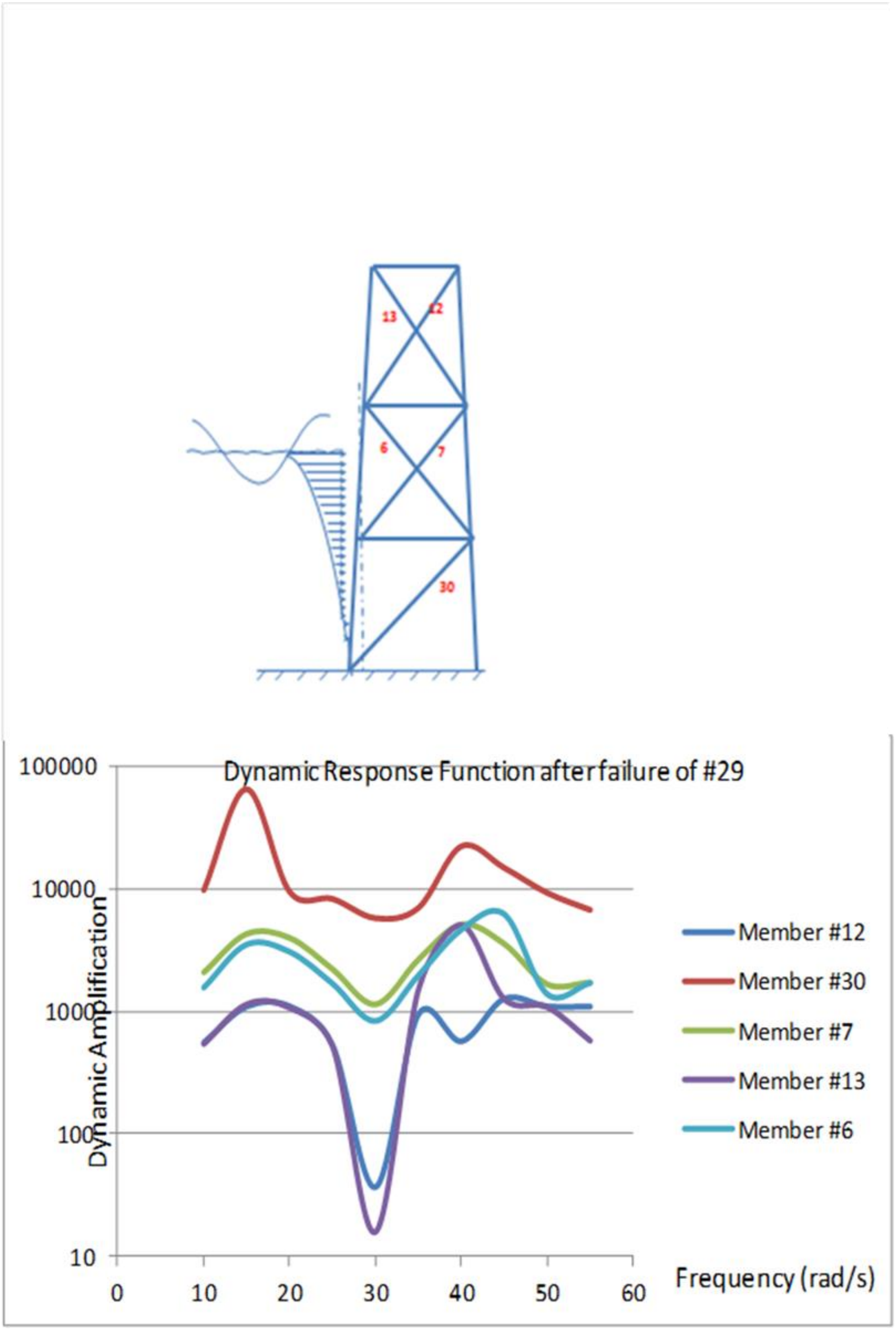


Figure 20. DRF of simulated structure with failed pair of bottom members (Nwankwo, C., 2013)

As could be seen from figures 19 & 20, the DRF of the failed structure is significantly different from that of the original structure prior to failure. This analysis demonstrates that DRF monitoring could be used to analyse structural failure.

The trunk lines are made with steel and hence the use of DRF could be investigated for application for failure monitoring if intelligently designed. In the example described above the DRF was based on force and fracture failure and was evaluated for two bottom braces. The use of force and fracture failure cannot be applied on fluid evacuation pipelines using DRF as described above. However small leak holes which could be said to represent pipeline burst could be analysed in pipeline evacuation systems using the DRF concept. Some of the measurable changes caused by pipeline burst or continuous leak could be observed as vibration or sound. Hence vibration or noise signals generated during crude evacuation process could be used to generate DRF and by similar comparison used to possibly detect leak. The merits, demerits, and how the use of vibrations and acoustics could be used to determine the point of leak using the frequency response function is discussed below.

3.4.6.1 Acoustic emission modelling

Sound and temperature logging are proven technologies for detecting leaks within oil and gas wells. The oil or gas well is made up of pressure vessels within pressure vessels and hence any leak from an inside vessel (tubing) will be observed as a pressure increase on the outer vessel (casing). The tubing is designed to convey oil and gas within a pressure envelope that is determined by the reservoir pressure gradient. Where a leak occurs in the tubing due to erosion, corrosion, mechanical connection failure etc., the tubing pressure is transferred to the production casing. Since the production casing is of bigger diameter it may be unable to withstand the Well's closed-in tubing head pressure (CITHP), hence there is an urgent requirement for an investigation and a risk assessment. Such investigation is to determine the point of leak while the risk assessment is to determine some necessary actions to mitigate against loss of containment, according to Hazard and effect management process as documented on page 56, while planning for remedial actions to fix the identified leak. Such investigation could involve sonic or temperature logging to record minute changes in temperatures or sound while the well is flowing. Through this logging technique the source of leak could be precisely determined with great accuracy. A major enabler to this technology is the fact that most of the wells are vertical or slightly deviated such that wireline logging devices can be delivered with the aid of self-weight or aided with some sinker rod. Figure 21 is an example of temperature and acoustic log acquisition for leak detection in a vertical gas well in the Niger delta.

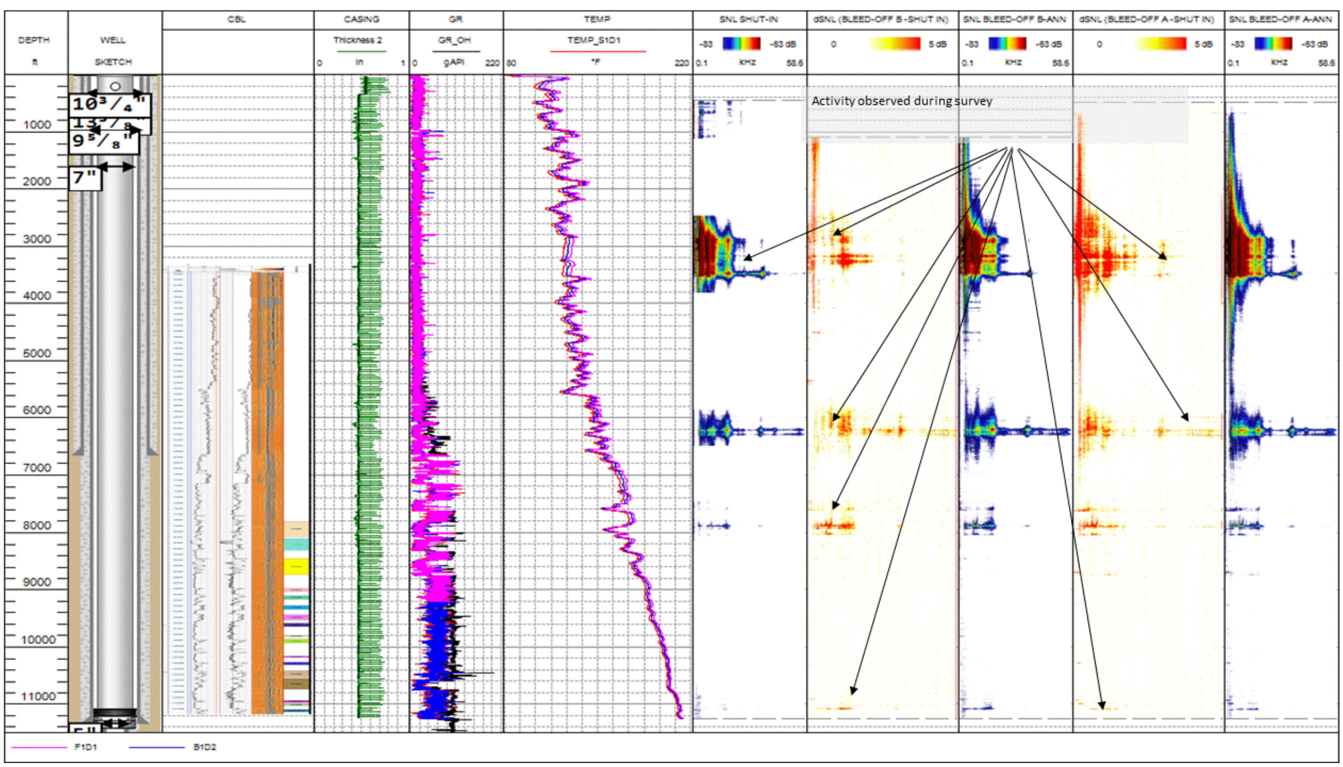


Figure 21. Temperature and acoustic logs acquired during leak investigation in a gas well.

As can be seen from the well sketch, the A annulus is the space between the 7-inch production tubing and the intermediate $9^5/_8$-inch casing while B annulus is the space between the intermediate $9^5/_8$- inch casing and the outer $13^3/_4$ -inch casing. The CBL on the log header is a log describing the cement bond logs between the casings and their respective formations. GR is the gamma ray log for the description of the sand and shale formations. TEMP is the temperature log at respective depths in degrees Fahrenheit. The problem in this well is that there is a tubing leak that led to a pressure in the A annulus which also led to an additional leak to the B annulus. To investigate the source of leak, a leak investigation programme was executed through log data acquisition inside the 7inch tubing. All logs are acquired while logging upwards. The first operation TEMP is a record of well temperature while well was flowing. Thereafter the well was shut in and a sonic log is recorded to listen to sound as shown in the different modes as described below:

- SNL SHUT-IN: Well shut in.
- SNL (BLEED-OFF B-ANN): Well shut in with B annulus pressure bled off.
- SNL BLEED-OFF A-ANN: Well shut in with A annulus pressure bled off.

The logs aSNL(BLEED-OFF B-SHUT-IN), and aSNL (BLEED-OFF A - SHUT-IN) are derivative logs used for the analysis of potential leak paths. The leak investigation reveals two large leaks between 2800 ftah and 3600 ftah and around 6300 ftah and two other minor leaks at 7900 ftah and 11050 ftah. This example documentation is to highlight that sonic logs is continually used to accurately locate leaks in oil and gas wells and make a case that such technologies could be applied to pipelines.

The advantage of gravity assisted logging opportunity does not exist in crude export pipelines as most export pipelines are horizontal or near horizontal. This therefore implies that the logging tools needs some form of conveyance system for internal trunkline acoustic or temperature log acquisition. These traction tools are available and used in oil and gas subsurface operations. Experiments have demonstrated that some form of traction could be applied as a form of intelligent pigging and used to drive noise or temperature logging tools for leak detection in horizontal pipelines (D. Lee et al., 2012; Nee et al., 2015). There are indeed tractors for logging of horizontal oil and gas wells. Unfortunately, the introduction of traction system to crude evacuation pipelines introduces some other problems. Any form of traction equipment, for example, requires some form of power and the development of intrinsically safe batteries for use inside highly inflammable hydrocarbon and is still an evolving technology that is not yet recommended (Recommended Practice for Occupational Safety for Onshore, Edition 2007). Also, such intrinsically safe battery still needs to pass the test of having enough power to convey the logging tool through the entire length of the pipeline which are usually in the range of tens of kilometres. Other considerations for internal noise logging in pipeline would be the risk of getting stuck and the need for production interruption for the launching and retrieval of these tractor conveyed logging tools. Even in situations where there is no major shortcoming for the application of logging for leak investigation on a pipeline, the fact that there is a loss of containment has already created a major emergency and hence the luxury of allowing the loss of containment to go on while planning to design a logging programme is unacceptable. This is in contrast to oil wells where the leak on the tubing is contained by the outer casing such that we can keep monitoring the effect of such leak on the casing while planning a logging programme to identify the leak source.

A similar effect of internal logging could be derived through noise sensing outside the circumference of the trunkline. So, if there is a way of placing the noise logging tools at several points external to the trunkline being investigated, then through these noise sensors leaks could be detected. This use of acoustic technologies for external pipeline leak detection has been demonstrated to varying degrees by several researchers (Ahadi & Bakhtiar, 2010; Ben-Mansour et al., 2012; da Silva et al., 2005; Davis & Brockhurst, 2015; Jin et al., 2014; Kam, 2010; Kim & Lee, 2009; P. J. Lee et al., 2005; S. Li et al., 2014, 2016; Majumder et al., 2008; Murvay & Silea, 2012; Tanimola & Hill, 2009; Yang et al., 2008). The most recent studies focussing on acoustic response function was documented by Ahadi & Bakhtiar 2010; Jin et al. 2014; Kim & Lee 2009; Li et al. 2016; Li et al. 2014; Tanimola & Hill 2009. Most of these research works are based on laboratory experiments and hence have not considered the background noise that could affect the acoustic signal due to hydrocarbon leaks. Such noise could be from moving vehicles and trains, tidal movements etc. There is also a need to consider noise attenuation in buried trunklines as well as how to distinguish the noise due to leak and those due to hot tapping process. The strength of this external acoustic technology could be harnessed and used to monitor hot tapping which is one of the objectives of this research. A major downside however is that this technology, while it could accurately determine the point of leak it would need a lot of auxiliary instrumentation to determine the rate of leak or stolen crude.

3.4.6.2 Vibration modelling

Some of the measurable properties of steel structures subjected to axial load are strain and deflection and these could manifest as vibration. Vibrations monitoring is one of the commonest studied technology for monitoring of structural health (Abdelghani & Benveniste, 2000; Colombo et al., 2009; Deraemaeker et al., 2008; Horizon & Group, 2011; Kopsaftopoulos & Fassois, 2010; P. J. Lee et al., 2005; S. Li et al., 2014, 2016). Past deployments of this technology focused on bridges, high rise buildings, and offshore platforms. This is primarily because such mega structures display movements which could easily be measured and amplified. This therefore enhances the use of DRF workflow for detection of deflection. However, the use of vibration monitoring technology for pipeline leak detection is still novel. This is primarily because vibration, as a response to stimulation, is an oscillation about an equilibrium point and hence a significant force, much more than the pressure pulses generated during crude evacuation on trunklines, is required to create any easily measurable vibration on large pipelines with diameters ranging from 12 to 36 inches. The pumping of crude oil through pipelines does not create the same level of oscillation on the pipeline as with vehicles travelling on long bridges for example as documented in research works. Also, because trunklines are large in diameter (12 – 36 inches in diameter) there is a limit to the evacuation pressure that could be applied to avoid pipeline burst hence there is a limit to the level of vibration during trunkline crude evacuation. This very minimal vibration will therefore demand extremely sensitive instruments for vibration monitoring. This is unlike the case during subsurface reservoir stimulation treatments where large treatment pressure in the range of over 3000psi are used to pump stimulation chemicals through small 3-inch chiksan pipes. The level of vibration in such stimulation operations are so large that steel ropes must be used to anchor the chiksans together and lock them to permanent fixtures to restrain them from "flying off" during such operations. Apart from the requirement for overly sensitive equipment, the measured vibration signals during crude evacuation in large pipelines also need to be magnified in other to reduce approximation errors. The major shortfall for the use of vibration technology however would be the number of frequency monitoring sensors required and how to distinguish the vibration signals where they meaningfully exist from the surrounding noise.

3.4.7 *Floating micro robots*

Robots are life mimicking mechatronic machines and could be autonomous or semi-autonomous. Overall robotic assistive strategy for condition monitoring, inspection and control strategy of sensitive oil and gas industry can be broken down into human–machine interface, data-signal transmission, resource allocation and task scheduling, navigation technologies, localization of the mobile robots and workspace-objects, inspection technologies and teleoperation etc. (Amit Shukla & Hamad Karki, 2016).

The use of pigs for cleaning and integrity monitoring has been discussed earlier while discussing corrosion as a suitable technique worth consideration in leak detection. Pigging is a normal operation in pipe transport technology where they are used to sweep service pipeline of sand and sediments. Smart pigging is an improvement over the normal pigging operations by combining some data acquisition capabilities for pipeline thickness monitoring. These surveillance operations involve the use of multi-callipers and sometimes acoustic tools (Vuen et al. 2015; Lee et al. 2012). It is suggested that the major disadvantage of production interruption requirement for intelligent pigs could be overcome with the use of floating micro robots which will not require launching and retrieval pads like pigs. Such micro robots, sometimes called free swimming leak detection system (Henrie et al, 2017), could be designed to flow with the crude being pumped and could be designed and operated to safely pass through the inlet valves of reciprocating pumps and gate valves before being discharged with crude at receiving tanks for reuse. Two options could be conceived for the use of this technology: 1) The robots mix with the crude and is retrieved at the terminal for data download and continuous reuse; 2) Where the robots are self-propelling and are programmed to travel as required for data acquisition either autonomously or for later download. This concept of floating micro robots would require that such floating objects must be properly sized to float on self-weight and properly mix with the fluid being pumped but this will create additional processing requirement for the retrieval of such robots at the terminal. Even in cases where these floating objects could easily mix and travel with the crude, the rate of travel could be non-uniform and hence difficult to predict surveillance location. The second option of using self-propelling micro robots will involve the use of intrinsically safe batteries for propulsion, communication, and data acquisition while the robots are in transit. The process of making an intrinsically safe, long lasting batteries could lead to increased weight to ensure that any battery spark or explosion is contained in a meticulously designed battery encasement. This additional weight may make the object unable to float. On the other hand, without such heavy battery encasement any micro spark from the battery during operation will ignite the pipeline which is always charged with hydrocarbon gases. There is also some assumption that, in both robotic cases, the pipeline configuration is such that GPS signals could be received throughout the pipeline length. Another major disadvantage of the use of proposed floating micro robots is the fact that they could be lost during transit as they are designed to flow with the fluid and hence could flow in the direction of fluid being stolen.

The use of floating micro robots could be very innovative as a concept but is currently being limited based on reliance on its ability to flow with the fluid being evacuated and huge dependence on battery for GPS auxiliaries, and sometimes propulsion, to locate the section of pipeline corresponding to the respective surveillance data acquired. Another thing worth considering is whether the data processing would be automatic or whether each returned floating micro robot will need to be processed for data download and analysis before being recycled. Some consideration should also be given for the time requirement in conveying one molecule of crude accompanying such floating robot over a distance of some 100km before data download for processing as this would also be a major disadvantage on the use of this technology.

3.5 Chapter summary

An under reported one thousand people have been killed because of explosions from leaks and vandalism on crude and refined product pipelines in Nigeria for the period 2004 to 2014. These lost lives add to an estimated monthly revenue loss of about £1bln by both the EP operators and the people of Nigeria. These human and financial losses have a double dipping effect to the people of Nigeria as the operators have negotiated a way of paying taxes only on the actual hydrocarbon exported. This therefore means that the government loses their own joint venture (JV) share of the stolen crude as well as the tax revenue accruable from IOC's tax payable on stolen hydrocarbons. This appalling operating environment in the Niger Delta also leads to forest and farmland devastation, air pollution as well as ozone gas releases during the process of refining the stolen crude. This situation therefore calls for an urgent action on how to use all available resources to stop pipeline vandalism and crude oil theft. The current surveillance technologies like ROW monitoring by security agents on land and swamp operations have proven to be ineffective.

A detailed literature review of potentially new technologies for leak and crude oil theft identification has been conducted and summarised. The fact that continuous hydrocarbon flow occurs through major export lines limits some technology applications for leak detection to those that do not demand production interruption. Crude oil theft detection could be achieved through performance trend deviation monitoring but this approach, while being able to detect the point of leak, may not be able to quantify the rate of leak or stolen crude. It is therefore immensely helpful to have some expectation of what ought to be flowing as this knowledge will aid any selected technology to determine both the location and rate of leak or stolen crude.

A major disadvantage of using fiscal reconciliation and surveillance technology is that they are both post-mortem approaches and hence oil theft could have gone on for a long time before scheduled reconciliation time. Multistage reconciliation could be employed if we need to know the area of leak position to some coarse accuracy, but this would require huge operational upgrade as additional process instruments may have to be installed.

The use of corrosion monitoring technologies could, when combined with other technologies like sacrificial corrosion probes, advise on the probability of leak but it is unable to detect pipeline vandalism or the rate of crude oil stolen or leaking.

Hydraulic simulation results have been shown to compare reasonably well with actual production if a properly calibrated model is used for event prediction. The most common data needed for hydraulic simulation operations modelling are pressures, temperatures, and flow rates. The question then is to find a way of measuring these key parameters during the crude evacuation process, without interfering with the operating philosophy of the crude evacuation process, so that the measured data can be compared with the model prediction result and hence determine the point and rate of leak or stolen crude.

The use of smart operations capability, which incorporates all the gains of hydraulic flow simulation, could be a particularly good fit to the research objective and could be used as a standalone technology or combined with flow simulation using digital twin to accurately determine leak point and rate of leak. The downside to this technology is that due to operations design limitations wet flow measurements for volume flow rate is still a challenge in oil trunklines. There are also challenges on how to deploy suggested pressure measurement points without compromising the installed pipeline integrity as every pressure monitoring point is a potential leak point.

The use of fibre optic technology does not quite meet the objective of detecting crude theft as this technology could easily be vandalised even when designed for leak detection and it is also incapable of detecting the rate of leak in an open environment.

The use of FRF or DRF modelling has been demonstrated as highly effective for the determination or prediction of potential failures for structures like bridges, steel structures and high-rise buildings. The deflections and vibrations from such structures are just sufficient for the estimation of FRFs that could be trended or trained to estimate the onset of failure. The vibration and acoustic signals generated during pumping operations could be modelled as FRFs and used for pipeline leak detection but the signal response from pumping operations may need to be over stretched to be able to use these technologies to determine leak position as well as the rate of leak or stolen crude.

The concept of using floating micro robots could be very innovative as a concept but is currently being limited based on considerably basic operational issues of transportation, data acquisition and several dependencies.

Having discussed the strengths and weaknesses of these selected feasible technologies that could be applied for leak and theft detection on pipelines some further analyses were made on how to rank them in other to determine which technologies, or group of technologies, that could be progressed further to detailed design.

4 TECHNOLOGY CONCEPT SELECTION

4.1 Introduction

The objective of this analysis is to synthesise the findings from literature review and progress a concept, or some concepts that could be further researched and used in the framing of a new process for pipeline integrity monitoring.

Crude theft occurs whenever vandals hot tap or illegally connect to the trunk lines so this exercise is designed to select any technology that could detect illegal hot tapping prior to crude theft, and also estimate leak point and the leak rate or theft.

Some evaluation criteria were therefore created to ensure the achievement of research objective of predicting leak point and leak rate through hot tapping and crude siphoning.

4.2 Technology concept selection report

A technical evaluation of reviewed technologies for leak and theft detection on pipelines was conducted to determine which technologies, or group of technologies, that could be progressed further to detailed design.

This concept selection exercise was to ensure that:

- The conclusions of the literature review have, within the trunk line operational framework and boundary conditions, scanned wide enough to identify all potential technologies for the achievement of research objective for leak monitoring, crude oil theft detection, and quantification of leak (or crude theft).
- All identified technologies are capable of being used to achieve the research hypothesis which states that; ***If we have a way of continuously measuring the steady state conditions***

at regular intervals (say 5km or 10km) on a given pipeline during operation, then we could, through deviations trending from the steady state operation, determine the point of leak or crude oil theft and quantify leak rate or theft.

- The literature review has identified all potential risks, opportunities and mitigation plans associated with each potential technology that could be progressed to concept selection stage.
- Any selected technology is technically robust or would require minimal refinement to meet the research objective.
- All non-technical risks (NTRs) like sabotage in the Niger Delta operating environment were sufficiently considered during the technology selection process.
- Key uncertainties like varying crude flow rates, pressures and temperatures were considered in the technology selection process.

Economic screening will, where necessary, be used as a discriminator where several technologies demonstrate capability of meeting all the research objective. Some of the factors to be used to evaluate the investment in this research, or the implementation of any useful finding therefrom, would include the cost of crude oil stolen and the value of lives lost on one hand and the cost of the deployment of the proposed smart process on the other hand. The cost of lives lost could be quantified based on the age distribution of the recorded death statistics and the value the dead would have added as GDP based on average remunerations and life expectancy in Nigeria. But is economics really a limiting factor in the search of an utterly new solution as discussed in Pathway to knowledge innovation? A research is purely a technical solution to a known problem so somehow there are inbuilt economic indices in the fusion of ideation, inspiration, and implementation to yield the required technical innovation where appropriate. Therefore, a standalone economic analysis may not be needed except where two equally probable technical innovations exist.

In other to ensure that this research delivers a product that could address the documented research hypothesis, all key issues highlighted in the research objective were assessed using the following evaluation criteria:

- Ability to detect leak.
- Ability to detect pilferage.
- Ability to estimate rate of leak.
- Ability to detect hot tapping locations.
- Whether proposed technology could be data driven.
- Suitability to trunkline operating environment (OE).
- Technology maturity.
- Ease of repair and troubleshooting during failures.

Some weightings were assigned to these evaluation criteria based on criticality. The extent of achievement for these respective evaluation criteria were graded using the traffic signage system (green, yellow & red) as well as number grades. Ten (10) points are assigned where a criterion is fully met (green), five (5) points are assigned to partially met criteria (orange), while zero (0) point is assigned where evaluated criteria is not met (red). The results of the technical evaluation of the reviewed technologies are as shown in table 1.

Table 1. Technology screening table

	Evaluation criteria	Weight %	Potential Technology							
			1	2	3	4	5	6	7	8
1	Ability to detect leak	15								
2	Ability to detect crude theft	15								
3	Leak rate estimation	15								
4	Hot tap operation detection	15								
5	Data driven technology	10								
6	Suitability to OE	10								
7	Technology maturity	10								
8	Ease of repair or troubleshooting	10								
	Total weighted score	**100**	**50.**	**25.**	**60.**	**80.**	**60.**	**75.**	**75.**	**52.5**

1. Fiscal Reconciliation
2. Corrosion Monitoring
3. Flow Simulation
4. Smart Field Operation
5. Fibre Optic Sensing
6. Acoustic modelling
7. Vibration Modelling
8. Floating Micro Robots

It should be noted that the use of frequency response modelling could be achieved using either acoustic or vibration modelling. However, these two technologies (FRF using acoustic modelling and FRF using vibration modelling) were independently assessed in table 1 which shows the evaluation result of reviewed feasible technologies. The highest-ranking technology is the use of smart field operation.

The use of smart operations could therefore be considered as a key technology for the proposed technology solution for leak and crude oil theft detection. But crude oil theft only happens when vandals attach conduits through hot tapping. The smart fields operations, as was discussed in Smart fields operation section may be unable to detect hot tapping. Acoustic emission modelling and vibration modelling are the only two technologies capable of detecting the drilling process involved in hot tapping operations. These two technologies are equally ranked in this technology concept selection report. This decision point needs some trade off on the requirement for detection of hot tapping operation as a basic requirement. If detection of hot tapping operation is critical then some further research will be conducted on the use of FRF technology based on acoustics or vibration. On the other hand, we could downplay the requirement for hot tapping detection and progress further research on smart field operations. Smart fields operation was chosen based on ranking, so some further research was designed to close observed knowledge gap on smart operations for the development of a new smart process for pipeline integrity monitoring.

4.3 Smart fields operations synopsis

This smart fields operation synoptical documentation is necessary to explain the smart fields operations nomenclature as used in this thesis. Smart field operation builds on simulation as explained in section 3.4.4 on Smart fields operation literature review page 76. The basis for smart fields operations and digital twin is simulation and there are several levels of smartness or smart operations capability. Digital twinning, as documented in section 9.6.2 on Digital Twining in pipeline fluid evacuation process page 199, is the highest level of smart operations where the operational process or product is coupled with the digital simulator for receipt of both forward and backward signal information for data transmission, analysis and control for process or product performance optimisation.

If you have a subsurface hydraulic model which you update on yearly basis, as a minimum requirement, with BHP surveys from wells such a model can be described as a dynamic reservoir model. This is because you can update such model with time dependent data changes like annual production, current reservoir pressure and current fluid contact information. If the wells represented in such a model have sensors that can send real time data that are coupled with such a model for continuous update of such a model with regular production, contact and pressure information then we can say that we have a smart fields operation. Depending on the level of sophistication between the dynamic model and the real subsurface structure, we can use the created model which is now called virtual reality as a digital twin of the subsurface reservoir (actual object) which exists several kilometres below the see level.

The details of explored options for the development of a solution for leak detection are contained in Chapter 5 where the pre-leak data prognostic method and post leak data diagnostic methods were discussed. The post leak diagnostic method was eventually deployed using vector algebra as developed in section 9.3 on Pressure gradient vector analysis page 176 and selected for the development of the new smart process for pipeline integrity monitoring.

So, in summary the technology solution for the crude oil theft monitoring in the Niger delta was delivered based on vector analysis of real-time, online pressure measurements based on post-leak data diagnostic smart operations as represented in figure 22 below.

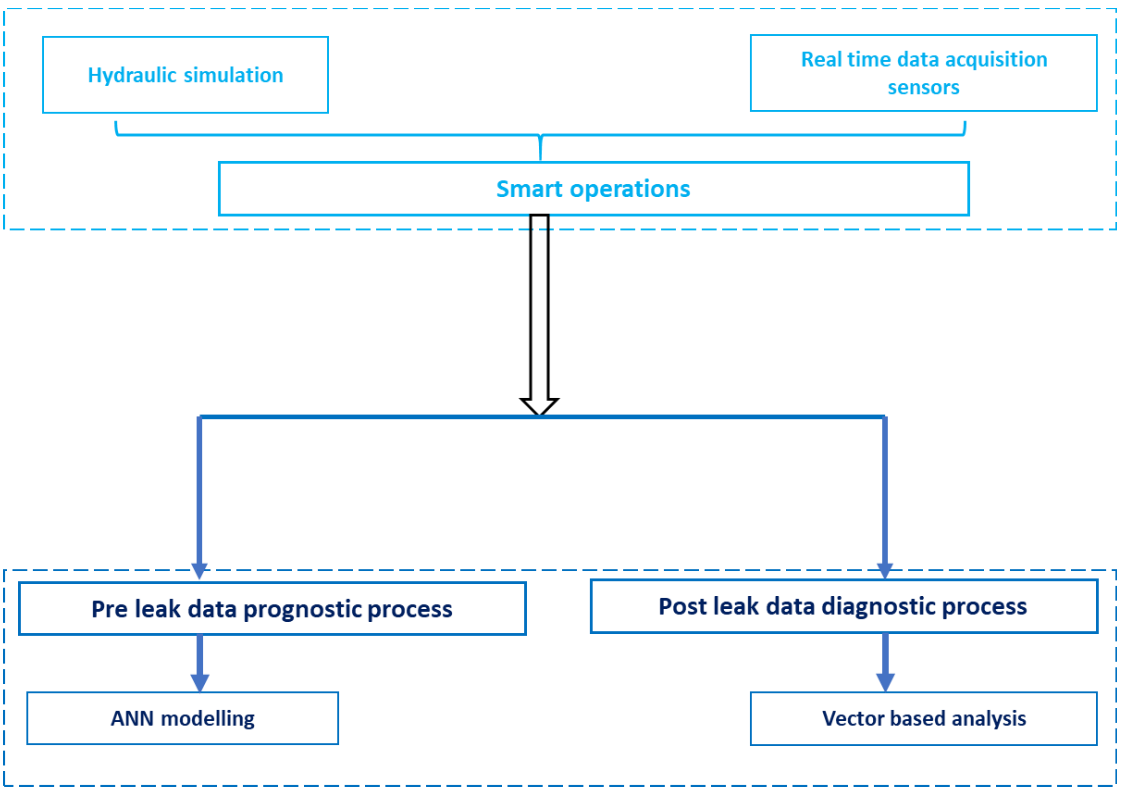


Figure 22. Smart fields operations technology progression path.

4.4 Chapter summary

The preferred technology for progressing this research is the smart operations technology which is an artificial intelligence workflow that uses instrument sensing, computer modelling, SCADA to partially perform human tasks aimed at reducing the decision cycle time for data-based decisions as well as managing production data uncertainties.

The artificial intelligence operation domain is huge, and the remit of smart operations is also wide. Some further study was therefore undertaken to find which aspects of smart operations that are more suitable for this research on leak detection or if there would be a need to combine more than one technology process in other to meet this research objective.

5 SMART PIPELINE INTEGRITY MONITORING REQUIREMENT

5.1 Introduction

Business organisations are made of knowledgeable persons appointed to execute specific roles regularly for the purpose of achieving an organisational goal. Operating procedures and standards are developed by such organisations to, among other things, help staff deliver quality and cost-effective products or processes. Where some of the organisational goals are designed to be continuously repetitive, such jobs could be outsourced where applicable, or designed to be executed by less experienced persons with the support of a few subject matter experts (SMEs). Such repetitive jobs could also be operated with numerically controlled (NC) machines or robots which are best suited for such repetitive, sometimes risky, and sometimes complicated jobs as could be seen in many industries. Some robots could be found in manufacturing plants, the automotive industry and in military service. Unexploded munitions for examples are retrieved and exploded by robots; unmanned aircrafts are extensively used for military data gathering and sometimes in delivery of bombs in high-risk war zones. Subsea remote operated vehicles (ROVs) are also used at seabed to carry out wellhead surveillance operations and some other oil and gas exploration jobs offshore as well as marine life exploration. Robots were also used in the delivery of food and medicines at some hospitals and remote locations during the fight of COVID19 pandemic in some countries. The development of robots is continuously evolving and even when business operations are fully operated by people, some of those operations are coded such that the use of AI is available as alternative guide to operators especially during potential process or system upset.

The result of this research literature review suggests that some benefits could be derived in terms of cost efficiency and HSE management if smart operations are applied to pipeline integrity monitoring. The expensive and current risky practice of using helicopter overflies to attempt to locate crude theft points over pipeline ROW of some 100 km could be eliminated for example. Although low level helicopter overflies yield good results in good weather, the downside is that the practice is expensive and the lives of the helicopter team are at risk as such helicopters could be shot down as have happened in Tanzania where a low-level helicopter chasing elephant poachers was shut down by the poachers in 2016 (The Telegraph, 2016). Another disadvantage to this current helicopter surveillance practice, which could be eliminated with a smart process, is the reduction in response time between suspected crude theft and the actual location of the crude oil theft point. A smart process has the capability for rapid and instantaneous location of the crude oil leak or theft point in pipeline as has been demonstrated in oil and gas wells which are basically vertical pipelines. It is anticipated that a new technology process could be crafted for leak point location and estimation of rate of leak without compromising the pipeline integrity nor increasing the cost of new pipeline installation.

It is believed that some of the possible reasons why smart operation are not already applied to pipeline crude transport process in the Niger delta could be endemic or economic. The world oil boom of the 1970s gave Nigeria a good developmental start-up as several oilfield projects and major civil facilities like ports and bridges were executed from proceeds from such oil boom. Over 15000 wells were drilled, completed, and produced in deltaic environment of about 75,000 square kilometres through pipelines to five oil and gas export terminals in Bonny, Brass, Eket, Escravos and Forcados. The subsurface hydrocarbon accumulation is considered the main asset being exploited and are usually developed once the projected revenue from recoverable accumulations can pay for all associated facilities like wells, processing facilities and pipelines in addition to operating costs. These Nigerian oilfield developments somehow happened without imagining that a country with such huge potential in the 1970s will degenerate to such a poverty level where crime and corruption will get to a level where pipeline vandals will brazenly be destroying oil and gas infrastructure. Even the IOCs operating in Nigeria never anticipated such and hence did not quite consider the security of their pipeline networks when they were initially built. Crude evacuation pipelines, other than major trunklines, which were originally not buried below earth surface, were hurriedly buried with the onset of pipeline vandalism but this action was already late. The pipeline vandalism which initially started as a way of showing dissatisfaction to government for lack of civil structures and past environmental degradation later developed into a huge industry for illegal crude theft for use in illegal refineries. The vandals upon realising how lucrative the illegal refining industry was, became sophisticated to the level of either paying corrupt government security agents for protection or having their own armed security agents. Several deaths have been recorded each time there is a confrontation between the government security agencies on one side who attempts to stop pipeline vandalism or illegal crude refining and these pipeline vandals on the other side who are defending their illegal enterprise.

Smart operations only gained momentum around the year 2000 in the Niger Delta, but the early efforts then were limited to only processing facilities and later to wells. The pipeline, within the E&P sector is considered a dispensable consumable hence not much emphasis was placed on making it smart or creating a smart process around it. However, with economic volatility, and several improvements in cost efficiency, any innovation that could lead to savings in any part of the EP value chain is welcome. This is another potential contribution to this work which emphasises the efficiency and cost effectiveness in the crude transport process. One approach to designing a data based smart process in pipeline transport process, based on use of deductive reasoning on pragmatist epistemology, would be to start with a hypothesis and then test such hypothesis using observed data to see if observed data follow some trends as proposed in the hypothesis. Another smart operations approach based on the same pragmatist epistemology would be to concentrate on observable data and use some axioms to form an explanatory model of the observed data. This later approach is based on inductive reasoning. The part for deductive reasoning and inductive reasoning are documented in section 2.4 on Research process page 50. These two smart operations approaches could be used to create a model of pipeline crude transport process which could be used to describe both normal and abnormal situations in the form of failure realisations. The realizations of foreseeable leak situations could be modelled, such that any future crude transport data could be matched to any of such model realization and used to detect anomaly arising from crude oil theft. The pragmatist epistemology, which can be used to support a suitable hypothesis, has been used to postulate that if we have a way of continuously measuring the steady state conditions of any pipeline at some suitable interval like 5km or 10km, or its immediate environment during crude transport operation, then we could determine the point of leak or crude oil theft at any section of the given pipeline as well as quantify leak rate or theft. On the other hand, the use of axioms which is also based on pragmatist epistemology could be used to postulate the relationship between cause and effect during pipeline crude evacuation such that deviations from known data trends, based on cause-and-effect relationship, could be used for the determination of anomaly in the form of leak or crude oil theft.

Any of these data driven smart operations methods could be used to frame a solution for the determination of leak or crude oil theft point in any pipeline system. The deductive reasoning approach to knowledge assumes that for any measurement to be useful we must have an idea of what we ought to be measuring. On the other hand, this fore knowledge is not particularly applicable if axioms are used as deviation monitoring from any given steady state data could give a qualitative indication of anomaly based on inductive reasoning. The creation of a system descriptive model (SDM) is needed in both methods such that any data from any future pipeline being investigated could be processed through such a model. A system descriptive model can be thought of as a mathematical attribute for describing the relationship of key variables responsible for system parameters such that the SDM can be used in future for prediction of desired parameters. A well system descriptive model for example could be used to determine well flow rate as currently flowing and how the flowrate would be impacted due to loss or gain in productivity index. It is imagined that a pipeline SDM could be created and used to monitor the performance of a pipeline without leak as well as for the prediction of how such pipeline would behave at different leak rates at different positions along the pipeline.

The main difference between the two pragmatic epistemological knowledge systems described above is that one is based on immediately acquired data (post-leak data based on deductive logic) from the pipeline being investigated while the other is based on past (pre-leak data based on inductive reasoning) environmental data from the pipeline being investigated or a similar pipeline in the past. In pre-leak processed methodology (inductive logic) the analysis focuses on events that could be assessed to have happened before a particular result is achieved. For example, you need to excite an electric conductor coil with some electric current before you energise a magnetic field, or you need to have punctured a pipeline before a leak can be established. In post leak processed methodology (deductive logic) we focus on current results to determine the preceding events. Applying post leak processing methodology on the same set of examples above, we could say that if an electric conductor coil is able to energise a magnetic field it means that there is current flow in the coil. We could also say that if there is a leak on a pipeline it means that the pipeline must have been punctured. In both cases you could process any newly acquired data through an SDM model that was created from either a pre-leak or post leak data in other to analyse such data. The ability to create an SDM with the available Niger delta production operations data using a pre- or post-leak data was therefore investigated.

5.2 Digital Twining concept

The pre leak and post leak approaches described above are technology corollaries using the same concept of SDM and can be represented using technology digital twin (DT) respectively at different levels of sophistication. A technology digital twin is a digital representation of a physical product, or process, in all its aspects:– from conception to detailed design on one hand and from construction through actual operations up to decommissioning on the other hand as depicted in figure 23 (Russell, 2019). Digital twining is used to continuously close the gap or optimise performance, using feedback and feedforward loops, between ideation (concept, design, or model) and a physical product or process (as built, as modified, operated, or as decommissioned). How do you use the data from your product to modify your idea or how do you use the data from your modified idea to create a better product or process? DT allows us to do things faster in the form of simulation instead of prototyping and could allow simulation of many models based on AI during the conception stage and the use of real data during operations or maintenance stage to create a more representative model (Grieves, 2015).

The complete innovation cycle for any product or process is made up of value creation (VC) phase and value realisation (VR) phase. The phases of value creation are: IDENTIFY; ASSESS; SELECT; DEFINE; and EXECUTE while the phases of VR are: OPERATE; MAINTAIN; ABANDON and DECOMISSION. The model (virtual space) and the actual products (physical space) can be continuously linked through data sensors for the purpose of performance optimisation in digital twinning during all phases (VC and VR) of product and process development.

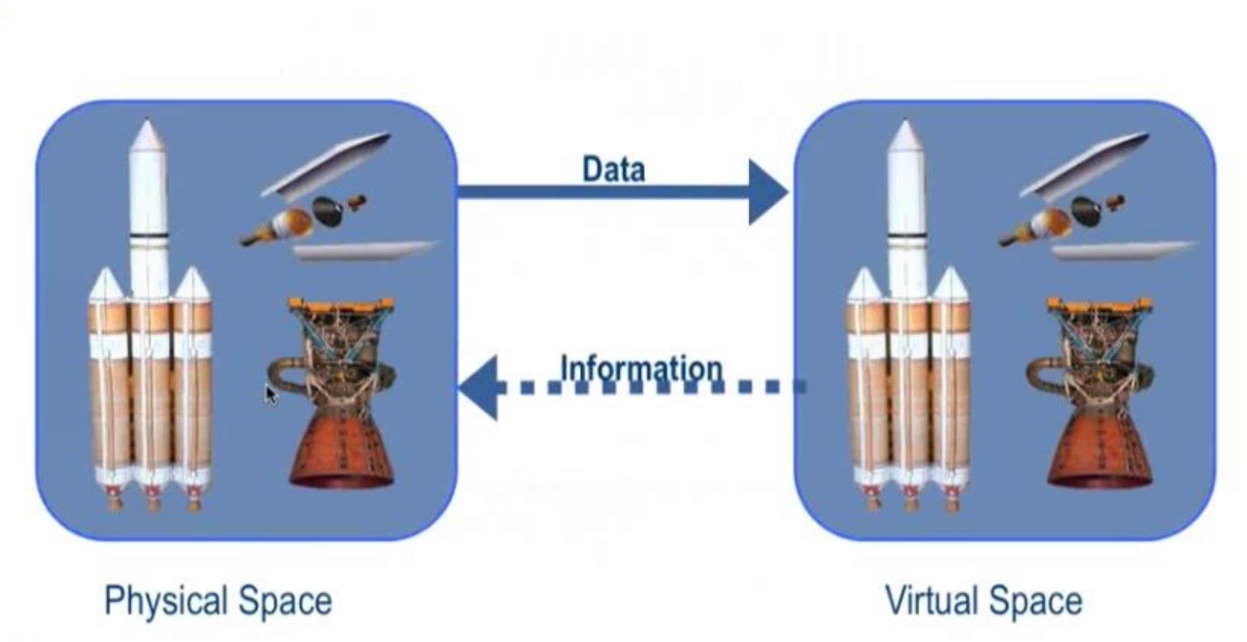


Figure 23. Technology virtual twin during operate phase. (Grieves, 2015).

Any created product could be equipped with several sensors for critical data monitoring and transmission of such data to the virtual models for continuous analysis and feedback to the product which can be in service at different locations anywhere in space. As a result of virtual twining, quality control (QC) engineering does not have to depend on failure analysis after a product has failed. With the modelled DT, operators can know ahead of time, through monitoring sensor data streams, when a particular component is about to fail, and designs can be improved such that through some inboard controls a failing component can be isolated if there are spares within the product during operation.

Both the pre leak and post leak methods are artificial intelligence methods for leak detection based on causal reasoning and a respective VR digital twin, and any of these approaches can be created using the defined SDM. Artificial intelligence (AI) will take digital twins to the next level with the ability to assimilate, analyse, simulate, predict, prescribe, and act with minimal human involvement – from digital twins that integrate data from various sources to one capable of acting autonomously as shown in fig 24 below (Russell, 2019).

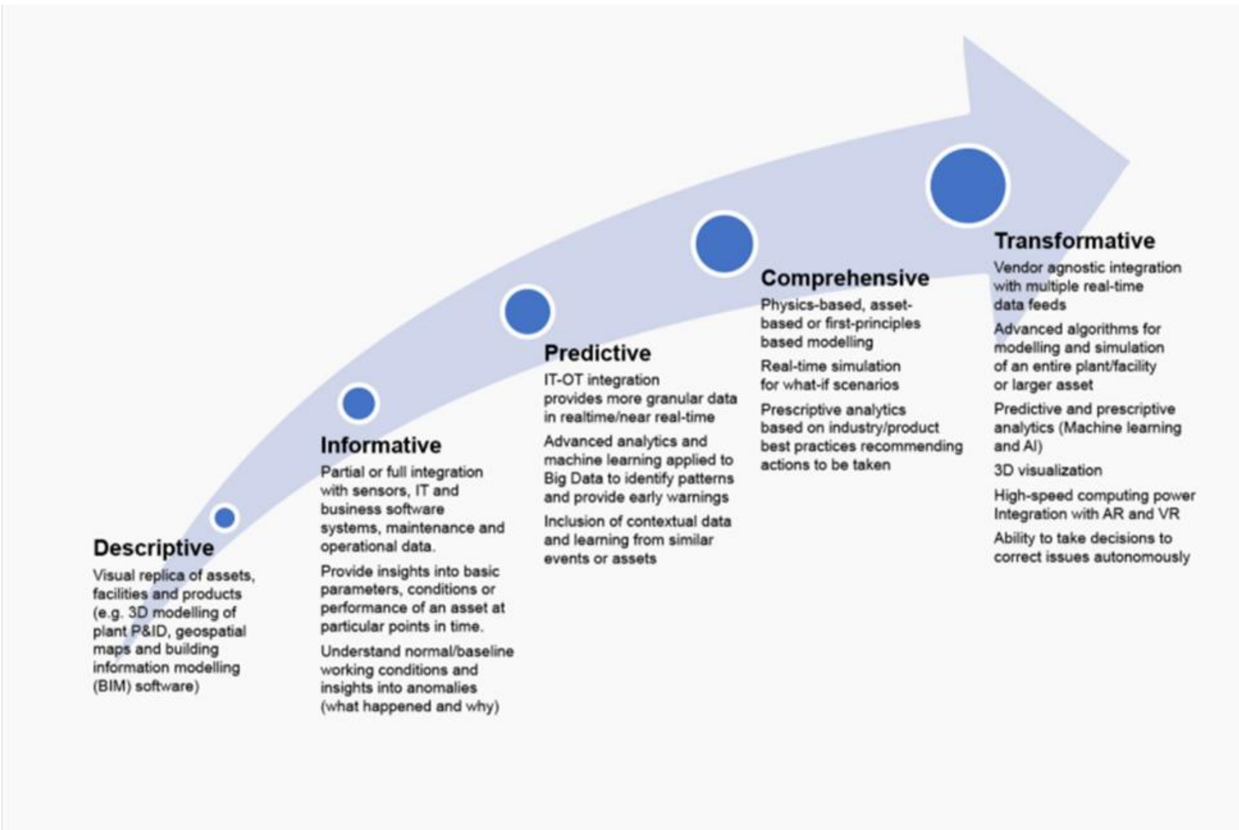


Figure 24. Digital twin sophistication levels (Russell, 2019).

One can say, from figure 24, that the pre-leak data SDM can be used to model an *informative digital twin* while the post leak data SDM can, if properly used to train a neural network or similar technologies, could be used in leak detection using a *predictive digital twin*.

A research mind map that highlighted all the issues that needs to be addressed has been presented in Reflexivity, positionality and research mind map. These issues were used for technology scouting through literature review which eventually yielded smart operations as a potential technology lead that can be used in meeting this research objective of helping to stop the menace created by crude theft environment in the Niger Delta. As with most research efforts we have an idea of what a technology solution could be but the pathway to this solution, if eventually achievable, is only attained through some doggedness. This dissertation, which eventually delivered a new smart process for pipeline integrity monitoring, followed a rigorous but sometimes flip-flopping map on technology leads of either using the pre-leak or post-leak smart operations process as documented in the solution pathfinder mind map.

5.3 Solution pathfinder mind map

This research involves a systematic study of issues relating to crude oil theft during pipeline crude evacuation in Nigeria: how the theft is achieved through hot tapping; how to analyse available data; how intrusion prevention or detection processes can be engineered; how similar problems are solved in similar and unrelated industries, and how conclusions can be made on how to contribute to some form of solution.

This research is made up of two parts. The first part, as described in Reflexivity, positionality and research mind map, dealt with problem definition, selection of research process and review of available literature that could provide leads for investigation for solutions to the menace created by crude oil theft in the Niger Delta. The second part, described in figure 25 by a more comprehensive solution pathfinder mind map, builds on selected concept of smart operations technology solution and involves progression of leads until such leads are no longer feasible or a solution to the new smart process on pipeline integrity monitoring was achieved.

Two approaches to smart operations technology workflow for the achievement of documented research objective were investigated. Both approaches are, as documented in section 2.4 on Research process , page 50 are based on:

- Hypothesis
- Data observation
- Confirmation of hypothesis

One approach would be to start with a hypothesis and then test such hypothesis using observed data to see if observed data can be used to support the hypothesis. The other approach would be to theorize on observable patterns, then test available data for conformance and where appropriate create a theory or hypothesis. The main difference between these two methods is that one is based on post-leak processed data while the other is based on pre-leak processed data. Pre-leak data process is prognostic or prescriptive and can be investigated using causal reasoning or artificial neural network modelling to highlight probable area of leak and estimate leak rate. Post-leak data analysis on the other hand is diagnostic and uses pipeline characteristic attribute like transmission pressures during crude evacuation to highlight leak point and estimate leak rate. The post leak data diagnostic method, if used to train a neural network or similar technologies, could yield a higher level of data twining sophistication than the pre-leak data prognostic process as shown in figure 24.

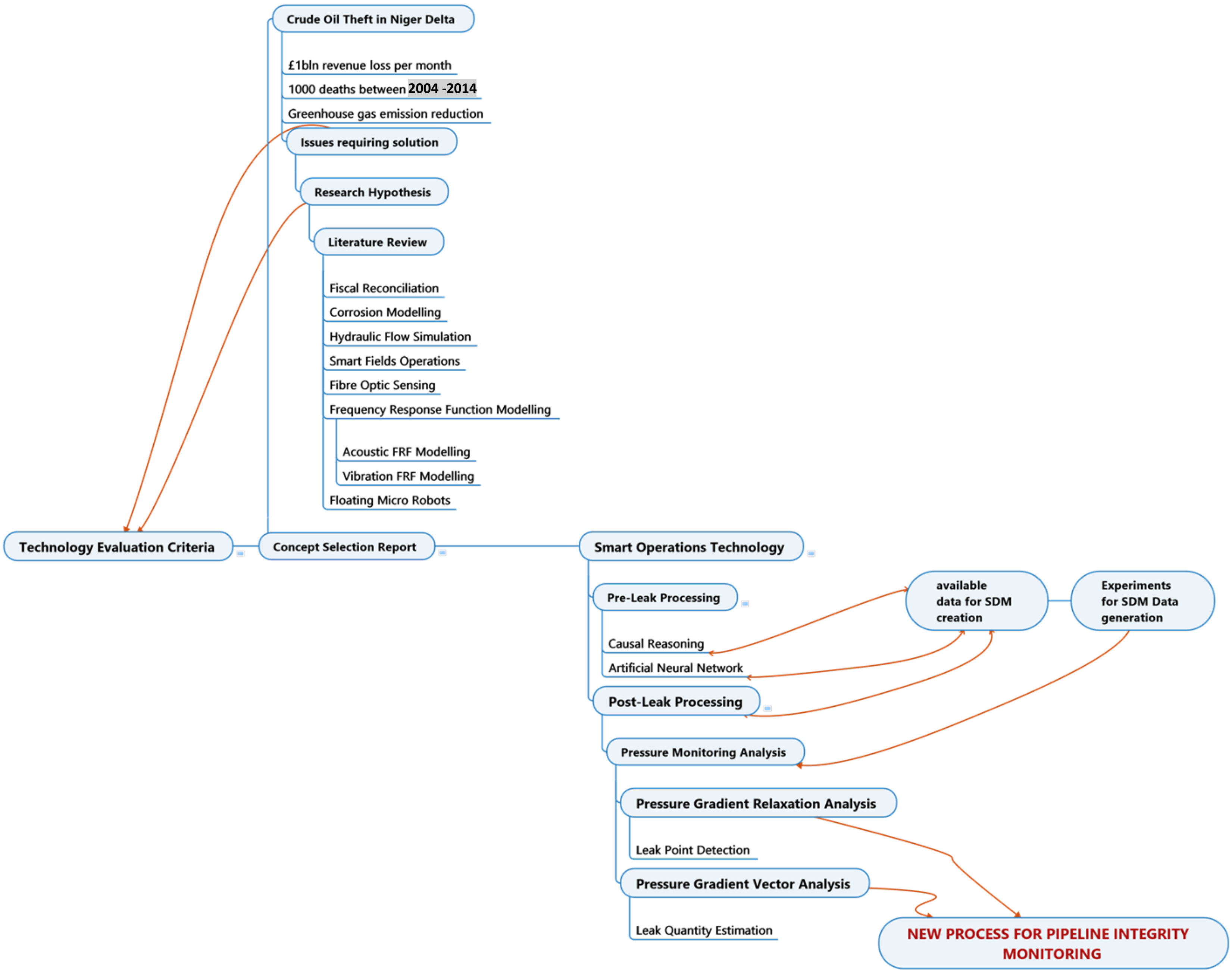


Figure 25. Solution pathfinder mind map

Both the pre-leak prognostic and post-leak diagnostic processes build on some form of system descriptive model hence some attempts were made to test the usability of some data already collected before the commencement of this research. This initial data synthesis revealed that the initially collected data are not useable for pre-leak data processing using artificial neural network. The collected data is usable for post-leak-data processing but has very limited output data. E.g., evacuation pressure values are only measured at very few intermediate points between the inlet and outlet. This therefore necessitated some simulation to reprocess the available data and regenerate transmission pressure profile to the required intensity. These simulation experiments were based on the initially acquired data but were used to generate data sampling points for the monitoring of transmission pressure which was the only data needed for progression of this research question of trying to locate point and quantify leak rate through pressure monitoring only.

The research hypothesis, which states that "If we have a way of continuously measuring the steady state conditions of any pipeline at regular intervals (say 5km or 10km) during operation, then we could, through deviations trending from the steady state operation, determine the point of leak or crude oil theft and quantify leak rate or theft", was therefore verified through pressure measurements using the post-leak data diagnostic process.

Through some pressure gradient experiments, it was demonstrated that leak points can be identified through pressure gradient relaxation while the leak rate at the respective leak point can be determined through pressure gradient vector method. The details of how the above research solution pathfinder mind map was used to arrive at the proposed new process for pipeline integrity monitoring are presented in the remaining part of this dissertation which is based on the selected smart operations technology workflow as documented in section 4.3 on Smart fields operations synopsis page 101.

5.4 Post leak data diagnostic method

Post leak data diagnostic method, as defined in this thesis, focuses on system result, and tries to investigate why any observed result corresponds or deviates from anticipated system conformance or anomaly, respectively. The pragmatic approach assumes that we know what ought to be flowing and hence relies heavily on measurements for the comparison of what is flowing against what ought to be flowing. Hydraulic Simulation provides an accurate account of crude throughput and could be used for the estimation of what ought to be flowing through any closed system used for crude evacuation. This approach is cheap if we have measurement at regular intervals along the pipeline length. It should be noted here that the frequency of such measurement is tied to our desired level of accuracy. A near perfect (100%) accuracy in leak point determination was achieved but a 93.44% average leak rate prediction accuracy was demonstrated based on the proposed smart process for pipeline integrity monitoring. The spacing between monitoring points (5km or 10km) would therefore have some effect on the leak rate prediction accuracy. Direct fluid measurement uses known techniques for measuring flow rates, temperatures and pressures through sensor's mechanical contact with the fluid stream while indirect fluid measurement relies on some effect of the fluid flow like heat transfer, eddy current effects, vibration and acoustics on their environment. Indirect measurements have been discussed as novel in large pipelines as measurement sensitivity and repeatability are not yet well established. Other issues hindering the application of indirect measurements would be how to distinguish flow induced signals from those due to background noise or how to prevent ground or underwater attenuation from masking measurement signals.

Direct fluid flow measurements are well advanced but is not permissible within the trunkline crude evacuation systems because such measurements create obstructions to the flow conduit area. Current oilfield measurement practices in the Niger delta require that flow measurements be made at two or three points along major pipeline: flowstations; major manifolds and export terminals. These measurements are used for estimation of reconciliation factors which are thereafter used in the estimation of production losses due to leak or crude oil theft. The shortfall of this limited data reconciliation approach would be that, even though we could estimate some losses, we are not able to estimate the exact location of alleged leak or hydrocarbon theft. This huge uncertainty associated with monitoring a long trunkline, for example, using only three measurement points could be reduced with increased measurement points. But any attempt to increase the data acquisition points also leads to increased risk due to additional flanging as these additional flanges are potential leak points. Non-routine, non-intrusive measurement systems using clamp-on equipment on the pipeline being investigated could be used to overcome these direct measurement challenges, but indirect measurement technology maturity is still at its infancy for several reasons. The primary reason being the validity of the signal correlation upon which such measurement is based and sometimes the need for continuous calibration of such signals. Also, any indirect measurement assumes that the pumping process will continuously generate strong signals which could be amplified and used to derive some form of measurement. The most commonly used non-intrusive, non-obstructive measurement systems in pipelines are based on sound sensing; vibration sensing; temperature sensing; and electro-resistive sensing tools which are designed to be clamped onto a pipeline being investigated for data acquisition.

The use of vibration and acoustic sensing technologies seemed promising from literature review. However, these technologies still need further investigative work to address the following:

1. How to use indirect measurement sensors to measure what is flowing through any given section of any given trunkline with minimal management change control.
2. The use of signal amplification technologies to magnify weak signals.

3. How to distinguish between pump signals from environmental signals.
4. How to design a reliable calibration algorithm for the prediction of what is flowing with suitable certainty.

5.5 Pre-leak data prognostic method

Prognostic or prescriptive data analysis process involves the use of advanced analytics and machine learning to identify patterns and provide early warning of potential risk surrounding the subject being investigated. Pre-leak data prognostic workflow refers to a process of using some past data analysis of pipeline systems and its environment under operations to prescribe the outcome of a similar system under investigation. This environmental data analysis methodology focuses on all potential external incidents that must have happened as a precondition for any expected outcome to occur. In the case of crude oil theft or leak, this will focus on activities external to the pipeline being investigated that needs to have happened to create a variance between the total crude being received at the terminal and the total crude being pumped from the respective flowstations. Potential activities that will lead to crude oil theft or leak include operational leaks and pipeline vandalism for the purpose of creating leak or crude tapping point. Operational leaks due to corrosion or pressure mismatch has been discussed earlier so the focus now are leaks due to pipeline vandalism. This, notwithstanding, any solution that could detect leak due to pipeline vandalism would also be used to detect leak due to corrosion or system upset due to pressure mismatch. This pre-leak data prognostic workflow feasibility was evaluated using causal reasoning and artificial neural network (ANN) both of which are artificial intelligence workflows.

5.5.1 Causal reasoning

Causal reasoning definitions, limitations, and applications have been documented (Bowers, 2017). According to Bowers, causal reasoning is a post-learning cognitive process concerning cause and effect. Theories of causal reasoning may concern the structure of associations, how agents use such structures, or how that structure affects action. Applying this definition to leaks during pipeline crude evacuation the question them would be what (past) post-leak cognitive processing we can assess and model for future pre-leak data processing. The method advocated here built on analogues. E.g., can we use the past post-learning result of a pipeline that was hot tapped for crude theft to create a model, now called pre-leak data prognostic model so that the pre-leak data model can be used to predict location of future leaks at any particular location. It must be stated (Bowers) that causal reasoning (reasoning about cause-effect relations) is appropriately dissociated from causal learning (learning about cause-effect relations): "learning is concerned with a bottom-up analysis; reasoning, top-down. Although knowledge about how causal learning occurs bears on the study of the ultimate structure, and knowledge about this structure bears on study of the way it is acquired, an integrative research that combines analyses of causal reasoning with learning carry potential worth, their distinction should be born in mind. A theory of causal reasoning may be silent on learning, or vice versa, and so caution is warranted in drawing conclusions about one in the context of theory about the other".

One of the puzzles to be solved in the pre-leak data prognostic method would therefore be how to generate scenarios based on external environment that could be used to explain causes of crude theft such that through some form of modelling we could use such scenarios to analyse future systems and locate leak or crude oil theft point.

Some typical external cause and effect relationship for crude oil theft could be written as:

- Pipeline vandalism leads to hydrocarbon leaks.
- Pipeline vandalism leads to low reconciliation factor (RF).
- Illegal hot tapping leads to low RF.
- Loss of containment during crude oil theft leads to environmental pollution.
- Crude oil theft provides feedstock to illegal refineries.
- Crude oil theft leads to increased OPEX due to pipeline repairs.

The above relationships and other relevant ones could be represented as cause-and-effect diagram in figure 26 below:

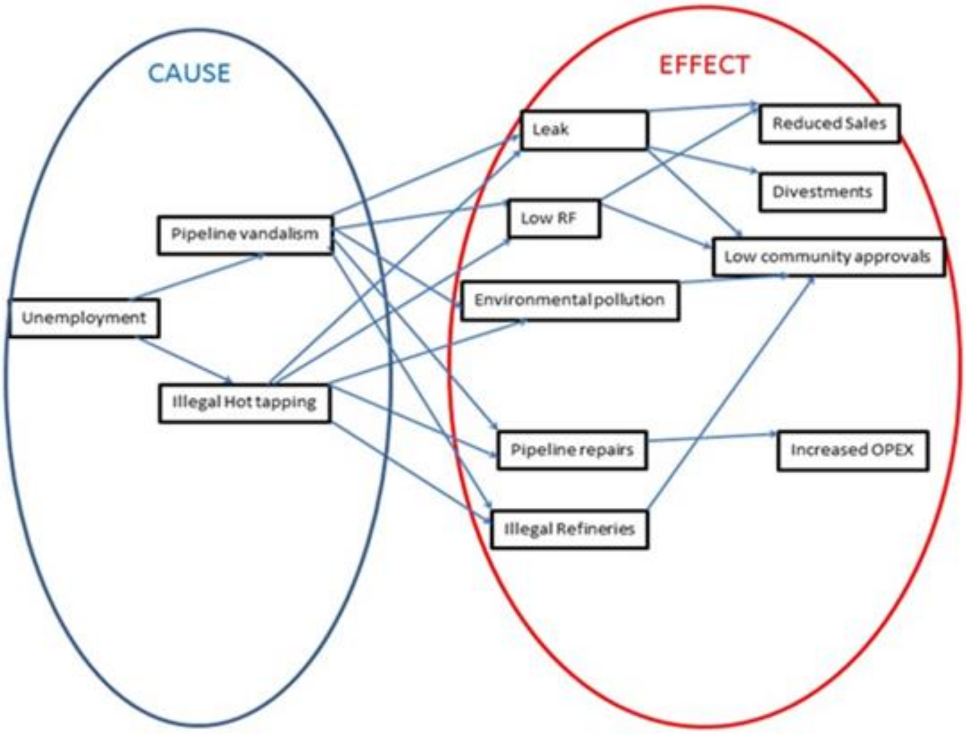


Figure 26. Pipeline leak cause and effect diagram

A simple attempt to resolve crude oil leak or theft in each pipeline can be demonstrated through some systemic approach using figure 27 which represents a section of a typical pipeline network.

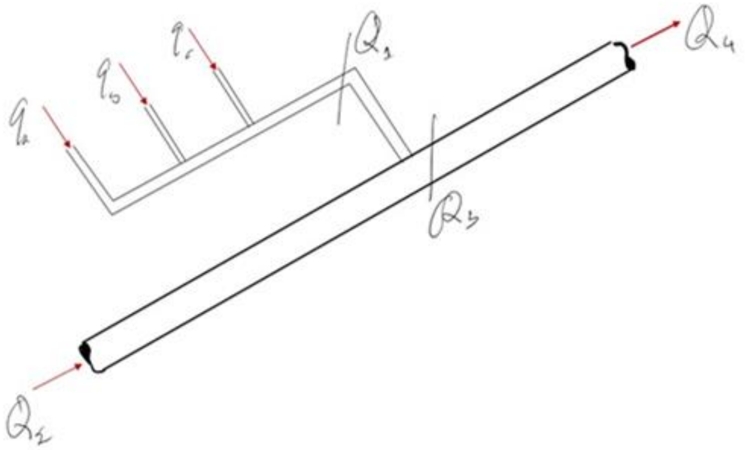


Figure 27. Pipeline sectional schematics for cause-and-effect demonstration

From figure 27 above the following flowrate equations and corollary statements can be made:

$$q_a + q_b + q_c = Q_1$$

so, if $Q_1 < (q_a + q_b + q_c)$ then there should be a leak or crude oil theft upstream of Q_1 .

Also

$$Q_1 + Q_2 = Q_3$$

and similarly, if $Q_3 < (Q_1 + Q_2)$ then there should be a leak or crude oil theft somewhere either between Q_2 and Q_3 OR between Q_1 and Q_3.

Similarly, if $Q_4 < Q_3$ then there should be a leak or crude oil theft somewhere between Q_3 and Q_4. This illustration was based on a simple evacuation system involving a section of a pipeline and explains how causal reasoning could be used to generate step by step deductions using *IF*, *OR*, *AND* combination statements.

Figure 27 represents a simple flow configuration example because it assumes that we accurately know the intermediate flow rates Q_1 and Q_3. Unfortunately, this is not the case in real flow situations. Any operational measurements recorded at Q_1 and Q_3 for example, may already have been influenced by some form of leak or crude oil theft upstream of those measurement points. Also, because there could have been leaks or crude oil theft downstream of these points, we cannot back propagate the intermediate flow values from Q_4 . So, in effect we have several potential leak points with just a few known input and output variables. The above discussion has highlighted a major disadvantage of causal learning (or reasoning), which is the fact that the interrelationship of multiple factors, especially with several unknowns are difficult to show or mathematically connect.

Also, the causal reasoning approach assumes that the solution provider knows all the causes of the problem being solved. This therefore limits the use of causal reasoning to qualitative analysis of thematic issues identification and hence may not be especially useful in the identification of leak or crude oil leak location and quantification using the pre-leak data prognostic method for leak prediction.

5.5.2 *Neural Network*

Unlike in causal reasoning, you do not need to have a detailed understanding of all the external environmental factors effecting any process being modelled in artificial neural network. It is just sufficient to demonstrate, based on the given pipeline environmental data approach, that a particular outcome is usually preceded by some events. With this knowledge, one could create a model that links a set of outcomes to some respective specific preceding events. Neural network therefore has some potential for this research objective and hence was also investigated. A typical neural network would have an input layer, some hidden layers, and an output layer. The hidden layer, for a pipeline crude evacuation process, will comprise all the factors that could affect the quantity and quality of crude being received at the export terminal. Such factors could be systemic or external to the pipeline being investigated. Systemic factors would include flowstation pump accuracies, shrinkage losses as gas comes out of the crude being transported, shrinkage losses due to temperature variations, small leaks at flanged or instrument connections. External factors include hot tapping for rogue conduit connection. A necessary condition for leak or crude theft would be that some intruders would have: 1.) gone to the pipeline; 2.) tapped onto the pipeline; 3.) connected rogue conduits to trucks or barges for illegal crude siphoning and 4.) sold or refined the stolen crude. Geographical coordinates are needed as a basic requirement to describe any pipeline under investigation. Such geographic pipeline boundaries could be sub divided into sections for more accurate prediction of output signal, especially when the pipeline is exceedingly long. The shorter the length of each subdivision, the higher the accuracy of the prediction result. The downside of having shorter sections and hence higher prediction accuracy would be the demand for more granular data input and demand for more computational processing power due to fine gridding.

5.5.2.1 Input Layers

The input data is a summation of all the crude pumped through the pipeline being investigated while the output data is the volume of crude received at the terminal. If the total volume of crude pumped are received at the terminal, then we could say that there is no effect of the hidden layers on the crude transport process. Otherwise, we could say that there is a leak hence the reconciliation factor could be assumed as a measure of the input layers. This is because the RF is a measure of the quality of all the crude pumped through the pipeline. The terminal RF is therefore an input data and a trigger point for the investigation of the hidden layers that causes the suspected leak or crude oil theft. Ideally, the RF should be equal to 1.0 as this implies that all the molecules of crude pumped from the respective flowstations are received at the export terminal. An RF of 0.95 is also acceptable, as the five (5) percent apparent production shortfall is generally within measurement errors and could be attributable to systemic losses like production shrinkage due to gas liberation and temperature variation. Indeed, this level of shortfall is not usually due to leak or crude theft. However, any other lower RF is investigated as due to leak. There is an oil industry regulatory requirement, as part of most jurisdiction's hydrocarbon resource volume management (HRVM) process, for throughput RFs to be computed on monthly basis. These monthly historical RF data are therefore readily available. However, there may be need to increase the RF data sampling frequency to weekly or daily as a way of reducing the response time to crude leaks and hence cut down on the amount of crude being stolen before the source of theft is identified and stopped. This same objective could additionally be achieved through intermediate reconciliation factor estimation between the flow stations and the export terminal. For example, you could have manifold reconciliation factors. These sectional RFs are also part of input layer because they provide information as to which section of the pipeline that is causing throughput shortage.

5.5.2.2 Hidden Layers

Any observed variance between what is pumped and what is received could only have been influenced by some hidden layers. The hidden layers are those factors, which could be estimated or measured at the environment surrounding the given pipeline or sections of the pipeline that could affect the output from such pipeline or pipeline section.

The following, based on the forgoing discussions, logic, and inferences, could influence, or could be studied to see if they correlate with data influencing crude theft:

- Loitering along pipeline ROW.
- Employment indices.
- Growth of illegal refineries.
- Automotive activities close to pipeline ROW.
- Periodic petroleum product shortages.

It should be noted, as discussed earlier, that the above influencing factors should be taken as philosophical postulations, based on cause-and-effect logic that could be tested. Why would someone, for example, be seen loitering along the pipeline ROW? A few of such trespassers could be harmless. But there are signs that reads “high pressure pipeline: please keep off” so this signage would discourage loiterers without evil intentions. There could also be hunters but the vegetation along the pipeline ROW is always kept low so could not really be a game neighborhood, except for a few hunters crossing from one thick vegetation to the other on each sides of the pipeline ROW. And of course, there would be vandals who are really interested in assessing the pipeline for hot tapping and crude theft and on the average, it is being postulated that these group would represent the bulk of the population of loiterers along the pipeline ROW.

A. LOITERING ALONG PIPELINE ROW

Some safe boundary distances of no permitted development are usually created on each side of any approved pipeline ROW to minimize human exposure during any loss of containment incident. As a result, oil and gas pipeline ROW are clearly marked as hazardous areas containing highly inflammable hydrocarbons under pressure. It has been shown that crude oil theft is undertaken by people through hot tapping. This therefore implies that if we have some form of data about people movement along the various sections of the pipeline being investigated, we could analyze such external data and use them in designing a pre-leak data prognostic model that can be used to see if there are correlations between people movement around any given pipeline ROW and crude oil theft on that given pipeline. One method of monitoring people movement is via satellite imaging, but this could be precarious in dense vegetation as well as expensive. Indirect measurements using phone signals could also provide some form of data. Access to people’s phone data is normally seen as compromising privacy laws but when compared against the £1bn being lost monthly to crude oil theft the Nigerian government could find a way of allowing security operative to use such data to monitor people that are loitering close to pipeline ROW. It should be noted that when closed circuit television (CCTV) was introduced it was initially challenged as invasive to people’s privacies but with time and consideration to public interests, especially in more developed nations, CCTV are now regular installations at public places and transportation systems like buses, trains, trains stations, roads and bus stations as a way of monitoring and controlling crime.

B. EMPLOYMENT INDICES

Crude pipeline vandalism initially started as a way of protesting lack of development initiatives by host communities but later grew into a lucrative business of crude oil theft. This lack of development led to gross youth unemployment in Nigeria and hence continual upsurge in crime. So, if we have data to show improvement in employment indices in the Niger Delta, such data could be used to corroborate any reduction in crude oil theft or vice versa. Unfortunately, reliable local employment indices are difficult to gather in the Niger Delta, especially at specific locations along the pipeline ROW. A plausible way of monitoring employment indices could be via access to mobile phone data, as data from a mobile phone user could be processed to create a model of respective user's personality. Most mobile phones have GPS monitoring tool and with such tool every movement of the user of such phone could be monitored and tracked. Some philosophical postulations that phone location stagnation could be used as an indirect way of measuring owner's productivity could be made. Any mobile phone that has not changed coordinates during the morning rush hours of 6:00 – 9:00am on a normal working day, for example, could possibly be said to belong to an unemployed person, a retired person, or to someone on some form of vacation. Registered telephone data also contains the age and sex of its owners and hence when such phone data are filtered on owners age, sex, hours of inactivity, the phones belonging to young unemployed youths could be further monitored to determine those whose nearness to any particular section of the pipeline always precedes crude theft from such pipeline. Also, with identity requirement for the registration of all phones in Nigeria, the exact identity of a particular individual whose nearness to a pipeline always precedes some form of crude theft on that pipeline can be precisely known through the activity log of mobile phones nearness to pipeline ROW.

C. ILLEGAL REFINERIES

Stolen crude oil are mainly used as feedstock for illegal refineries so if there is a way of monitoring the number of illegal refineries in the creeks, we could use some aerial environmental data to infer if there are trends between the growth of illegal refineries and crude oil theft in that area of the Niger Delta or vice versa. Since 2017 there has been some persistent smog in most parts of Port Harcourt city and one of the suspected causes of these smog are smokes from illegal refineries or smokes arising from fires created by air bombardments by government forces during the destruction of these illegal refineries. The black particulate matter in the atmosphere are giving some concerns to Niger delta residents, especially Port Harcourt, as most household furniture now turns black if left without cleaning within a day. The air composition is currently monitored regularly by government and the IOCs and the conclusions so far is not pointing to any source of pollutants. This air composition data could provide useful indicators on the level of illegal refining activities which is generally believed to be the main source of air pollution from public opinion. Unfortunately, only global data deductions could be made from these air particulate data about the level of crude theft if indeed it is proven that illegal refining is the source of most of the particulate matter. Even with this deduced indicator on illegal refineries, it is still difficult to synthesize these data to a level where they could be used to create a model for predicting crude oil theft.

D. AUTOMOTIVE ACTIVITIES NEAR PIPELINE ROW

Stolen crude is usually siphoned into trucks and barges from where they are transported to illegal refining sites or exported through ocean going vessels. Therefore, having some data on truck and boat movements would be a good input for pre-leak data prognostic model creation.

One option for monitoring truck movements in Nigeria could be via satellite imaging. Image recognition is a well-developed ANN process, and a process could be designed and trained to recognize and record trucks movement within a defined distance from the pipeline ROW under investigation. This approach will also be expensive and difficult to operate if it must be a dependable process data input to a new process for monitoring pipeline integrity.

E. PERIOD OF PETROLEUM PRODUCT SHORTAGE

There are three crude oil refineries with a combined installed capacity of about 450,000 bopd in Nigeria. These refineries produce at much reduced capacities due to breakdown or lack of proper maintenance planning and as a result refined petroleum products imports are regularly needed to augment supply even when the refineries are on production. This is partially because of gross lack of knowledge as to the exact data on daily petroleum product consumption in Nigeria. This lack of knowledge is partly because, based on Economic Community of West African States (ECOWAS) treaty of free passage of goods and services, petroleum products could easily be smuggled to neighboring countries. The federal government also claims that it subsidizes petroleum product distribution, and this also leads to corrupt inflation of petroleum import and distribution data so as to get money for distribution of products that were never imported nor bridged between regions in Nigeria. As a result of the foregoing there is constant fuel scarcity in Nigeria, especially during festive periods like Christmas seasons as a result of hoarding, or whenever any of the poorly maintained refineries is off production, or whenever the importation is interrupted due to exchange rate depreciation of the Naira, or sometimes industrial actions due to lack of government subsidies, or government refusal to pay import fuel subsidy which is an alleged channel for corruption.

An illegal refinery can be set up within days, so any prolonged period of petroleum product shortage automatically leads to increase in illegal refinery and hence increase in crude oil theft.

These Illegal refining are undertaken in jungles, so the current means of identification and combat is via helicopter overflies. The Nigerian military overflies seeks out smokes in jungles and combat them as appropriate. As a result of the foregoing, it is difficult to get any reliable data on the number and locations of these illegal refineries hence any form of modelling based on pre-leak data prognostic processing that relies on illegal refining data will be difficult to implement.

5.5.2.3 Output Data

Let us consider crude evacuation process where crude from six flowstations are pumped to an export terminal via two major manifolds as shown in figure 28. We could analyze a two-stage flow reconciliation process as shown, where measurements are made at the six flowstations (F1, F2…F6), two trunkline manifolds (M1 & M2) and an export terminal (T1). Using the ANN workflow, we could have hidden layers between the flowstations and the manifolds and additional hidden layers between the manifolds and the export terminal.

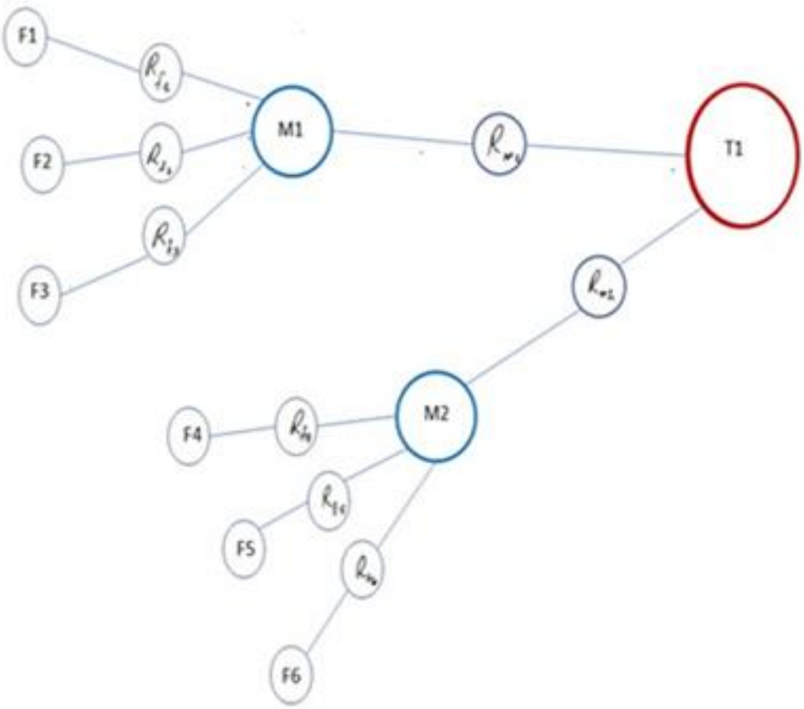


Figure 28. Pipeline network for reconciliation factor estimation

The ratio of the crude received at T1 to the sum of the crude being pumped from F1, F2, F3, F4, F5 and F6 is called flow reconciliation factor. This reconciliation could also be in two backward stages since there are measurements at M1 and M2. The first backward reconciliation would be the ratio of the crude receipt at T1 to the sum of the measured crude flowing through M1 and M2. We could also have reconciliation factors between M1, and the sum of the crude pumped from F1, F2 and F3. Similarly, we could have reconciliation factors between M2, and the sum of the crude being pumped from F4, F5 and F6. The distance between these flowstations and the terminal could be several tens of kilometers. This distance, its surrounding environment and activities therein would determine the integrity of the pipeline and hence what quantity and quality of crude that is received at the terminal T1. These activities that could affect the crude transmission could be represented as hidden layer(s).

As explained in literature review, the respective reconciliation factors RFs are created to account for losses which could be due to the hidden layers. Using ANN workflow, we can focus on the effect of the hidden layers to estimate the rate of leak or stolen crude at the respective sections of the pipe that will give rise to the respective R_{Fi}.

As a result,

$L_{F_1M_1}$ - Leak on pipeline between F_1 and M_1

$L_{F_2M_1}$ - Leak on pipeline between F_2 and M_1

$L_{F_3M_1}$ - Leak on pipeline between F_3 and M_1

$L_{F_4M_2}$ - Leak on pipeline between F_4 and M_2

$L_{F_5M_2}$ - Leak on pipeline between F_5 and M_2

$L_{F_6M_2}$ - Leak on pipeline between F_6 and M_2

$L_{M_1T_1}$ - Leak on pipeline between M_1 and T_1

$L_{M_2T_1}$ - Leak on pipeline between M_2 and T_1

The leak matrix would therefore be represented a 1 X 8 array of output leaks.

$$Leak = \begin{bmatrix} L_{F_1M_1} \\ L_{F_2M_1} \\ L_{F_3M_1} \\ L_{F_4M_2} \\ L_{F_5M_2} \\ L_{F_6M_2} \\ L_{M_1T_1} \\ L_{M_2T_1} \end{bmatrix}$$

Depending on the distance or desired accuracy of leak detection system we may subdivide each section of the pipeline into three parts and have a 1 x 24 array of leak or stolen crude position outcome.

The hidden layers would then represent the interaction of the six input layers with some hidden layers to give some twenty-four output that could be used to predict the probability of leak or crude theft point with some coarse accuracy at any subdivision of the pipeline being investigated as shown in figure 29. The result from this approach is statistical and in a one leak situation could be useful.

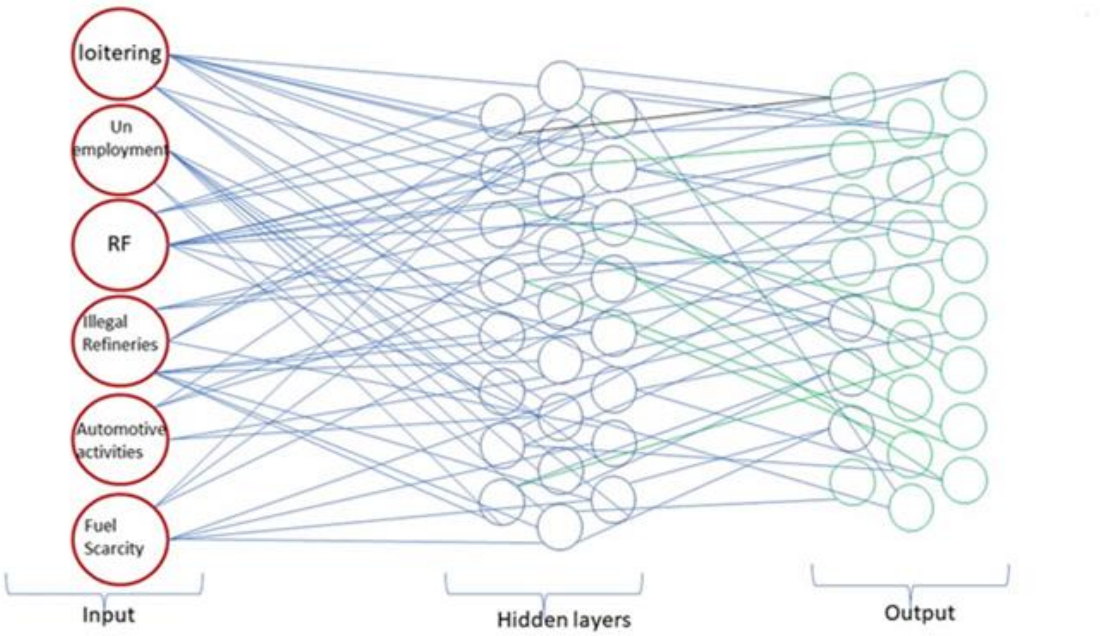


Figure 29. Pre-leak data prognostic ANN workflow for crude theft detection

5.6 Machine Learning

Machine learning (ML) is the study of computer algorithms that improve automatically through experience (BakIr, et al., 2007). Applications range from data mining programs that discover general rules in large data sets, to information filtering systems that automatically learn users' interests (Mitchel, 1997). If for example, we consider a set of data from some function which relates an attribute (y) to a variable (x). With two pairs of points (x, y) we can plot a straight line. If a newly acquired third set of points plot on the same straight line, then we could say that the dependency is a straight line. If unfortunately, it is clearly shown that such dependency is not a straight line, then we can continue with ML workflow to describe the relationship which can now be assumed as a polynomial. The actual curve (whether quadratic, hyperbolic, or exponential) will be perfected as more data become available until one gets to a stage where our guessed or assumed model will be able to perfectly predict future outcomes. This is the ML workflow which is seen as a subset of artificial intelligence where machine learning algorithms therefore build a mathematical model based on sample data, known as "training data", in order to make predictions or decisions without being explicitly programmed to do so (Koza, et al., 1996). Machine learning is therefore focused on two inter-related questions: “How can one construct computer systems that automatically improve through experience?” and “What are the fundamental theoretical laws that govern every learning system, regardless of whether it is implemented in computers, humans or organizations?” (Mitchel, 1997)

While it is not impossible to develop machine learning algorithm for leak point detection, the generation of required training data will take a long time and the luxury of such experimentation is unsustainable and unacceptable considering the loss of containment consequences. To achieve human level intelligence, learning machines therefore would need the guidance of a model of reality, similar to the ones used in causal inference tasks (Pearl, 2018). It must be stated that ML is an evolving discipline with extensive application in statistics and engineering. Some of the areas of ML applications relevant to this research include artificial neural network, causal reasoning, and testing hypothesis. It therefore implies that one can improve results of leak prediction and quantification as documented in post leak data diagnostic and pre-leak data prognostic methods for leak detection and quantification using the ML workflow. Such post-leak data diagnostic application of ML could be in testing hypothesis while pre-leak data prognostic data processing could be applied through improving SDM developed for causal reasoning or artificial neural network. As discussed in section 9.6.2 on Digital Twining in pipeline fluid evacuation process, page 199, ML can be used for transformative digital twining using either the diagnostic or the prescriptive analytics, hence the ML workflow is most suitable for the improvement of results based on pre-leak data prognostic (or prescriptive) method or the post-leak data diagnostic method.

The pre-leak data prognostic method currently has been assessed as difficult based on lack of data for SDM data twin creation. Also, the available post-leak data diagnostic SDM processing would limit the accuracy of leak point and rate prediction hence some further studies were undertaken on how to overcome the data gap for pipeline integrity monitoring through post leak data diagnostic method.

5.7 Chapter summary

The need for a data-based system descriptive model (SDM) and the potential use of such model for processing any new data for the determination of leak or crude oil theft in any pipeline system has been documented using some VR created data twins. Such model could be created based on pre-leak data prognostic or based on post leak data diagnostic method. Post-leak data diagnostic processing refers to the use of data generated by the pipeline system being investigated while pre-leak data prognostic processing refers to the use of external environmental data to the pipeline being investigated or a past environmental data from a similar pipeline. Post leak data diagnostic processing is instrument based and requires that we have some knowledge of what is flowing while pre-leak data prognostic processing is based on events surrounding the pipeline being investigated. The events which influence pipeline leak, based on pre-leak data prognostic processing has been documented as: terminal reconciliation factors; loitering along pipeline ROW; employment indices; growth of illegal refineries; automotive activities close to pipeline ROW; periodic petroleum product shortages. These data are difficult to generate in the Niger delta and hence makes the use of pre-leak data prognostic processing methodology difficult.

The pre-leak prognostic and the post-leak diagnostic processing methods are AI methods based on causal reasoning and can also be processed using data twins based on AI data feeds. Machine learning was introduced as a third AI method for leak position and rate estimation during fluid evacuation. However, ML algorithm for leak point detection was assessed as potentially luxurious as such experimentation would take an unsustainable long time to train but rather such ML workflow could be used to improve any SDM developed using pre-leak or post-leak data.

Post leak data diagnostic methodology seems promising since it is based on measurements. However, the current data acquisition practice in Niger delta, where only three-point data acquisition is applied, limits the level of accuracy achievable with post-leak data diagnostic processing. This inherent problem of post-leak data processing data paucity led to some further study.

6 DATA ACQUISITION STRATEGY

6.1 Introduction

The input variables suitable for Pre-leak data prognostic method workflow has been documented as reconciliation factors, local unemployment data, fuel scarcity, illegal refining data, loitering, and automotive movements. Unfortunately, the only measurable and readily available data in Niger delta, out of these six, is the historical monthly terminal reconciliation factor (RF). Local unemployment and fuel availability data are difficult to use in this analysis due to data paucity. Illegal refining data is also difficult as illegal refining occur in very thick jungles and mangrove creeks and any attempt at accessing these sites for data acquisition are usually met with armed conflicts. The conclusion therefore is that it is difficult to use the pre-leak data prognostic model for leak detection with only one reliably measurable data. This necessitated a revisit of Post leak data diagnostic method in other to devise means of overcoming its major short coming of data sampling inadequacy. This shortcoming arises because the trunkline conduit area is not designed to be obstructed with intrusive volume measurement devises. Unfortunately, external indirect volume measurement alternative solution using sound and vibration sensing devices on large pipes are still at their developmental infancy.

Our current knowledge of mass flow in a confined space requires the knowledge of pressure, volume, and temperature at any given position and time to describe any flow domain. If we assume isothermal conditions, we could ignore temperature variations and so the knowledge of just pressure and volume are sufficient to describe the propagation of the continuity equation. The pressure and volume dependencies during crude transportation were therefore simulated to generate the required data in support of an AI workflow for pipeline leak prediction using an SDM generated from the post-leak data diagnostic methodology as earlier defined.

6.2 Design of Experiments

The Niger delta oil patches cover a total area of some 75,000 square kilometres as shown in figure 30 (Erhimona, 2020; Whiteman, 1982) and with only five Hydrocarbon export terminals the respective hydrocarbons from these oilfields will travel a distance of between 50 and 200 kilometres through major trunklines, whose diameters range between 12 and 36 inches, to their respective oil and gas export terminals. Crude stealing through hot tapping occurs throughout the length of these trunklines as well as through delivery lines and some high-volume rate flowlines. A Niger delta trunkline and a delivery line were simulated as case studies with the belief that any finding therefrom will be universally applicable to any pipeline used for fluid evacuation. The simulation design objective was to find how to generate additional data through reprocessing of existing field data for leak identification, as well as quantification through pressure measurements only.

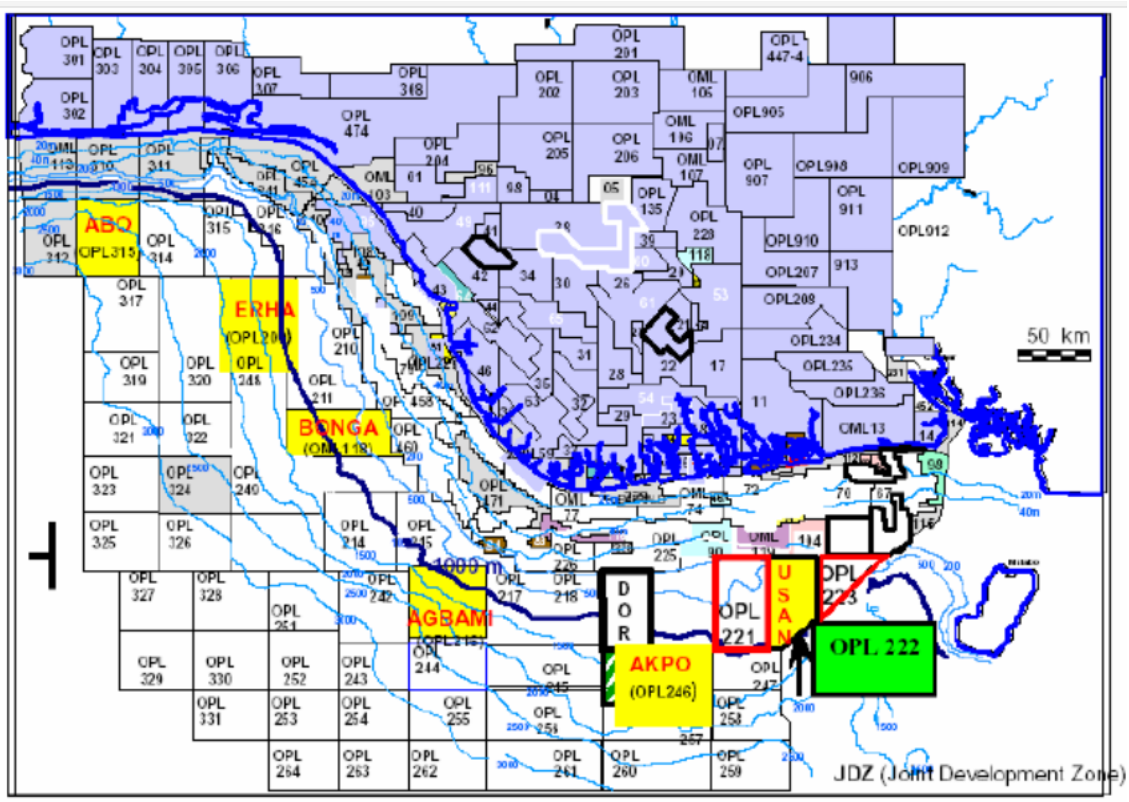


Figure 30. Niger delta oilfield acreage map

6.2.1 *Basis for design*

A narrative of fluid evacuation through a given pipe length is presented here as a basis for design of experiments and how pressure response from simulated leaks from such conceptualised experiments will be used. Let us consider an imaginary 10km, 6-inch pipeline with an inlet pump pressure of 300 psi and a 0.02psi pressure loss per meter. The 10km pipeline could be divided into ten (10) equal parts for pressure monitoring during the fluid evacuation process. A plot of the pressure profile during the pumping process will represent a straight line from an inlet of 300 psi to an outlet of 100psi and all anticipated pressures at any of the pressure monitoring points will align with the inlet-outlet pressure profile. Any leak simulation experiment at any of the section will create a deviation from the developed trend. It can be demonstrated that the degree of deviation is directly proportional to rate of leak or pressure loss. This pressure trend alignment and deviations formed the basis for the design of experiments for data generation in support of this study.

6.2.2 *Simulation setup and strategy*

One way of generating the required post-leak diagnostic data could be through fluid evacuation experiments using a mechanical test rig. This would be expensive and time consuming. The use of such rigs has been researched and quite useful (Abdulshaheed et al., 2017; Covas & Ramos, 2020; Gong et al., 2014; Lossouarn et al., 2016; Ostapkowicz, 2016). The methods used by these researchers includes acoustic sensor data modelling. Unfortunately, the use of acoustic sensors has been discounted as unusable for data gathering in operational pipeline systems (page 86). A cheaper alternative to the use of mechanical test rigs involving the use of computer simulation was selected as this approach has the required capability to adequately model the exact dimensions, configuration, and pressure settings of any required pipeline case study.

A conceptual simulation setup is as shown in Figure 31 with the pipeline being investigated having boundary sections at P_{inlet} and P_{outlet}. In other to simulate leaks or crude oil theft, ten (10) leak points were attached with suction pumps on the pipeline under investigation. Intermediate pressure measurement points (not shown on diagram) were attached to record downstream pressure after each leak point. These pressure gauges monitor the pressure response to simulated leak rates during continuous pumping process from the reservoir through M_{valve} and T_{valve}. This model setup would have the capability to simulate single leaks at selected sections as well as multiple leaks at several combination of sections of any pipeline being studied.

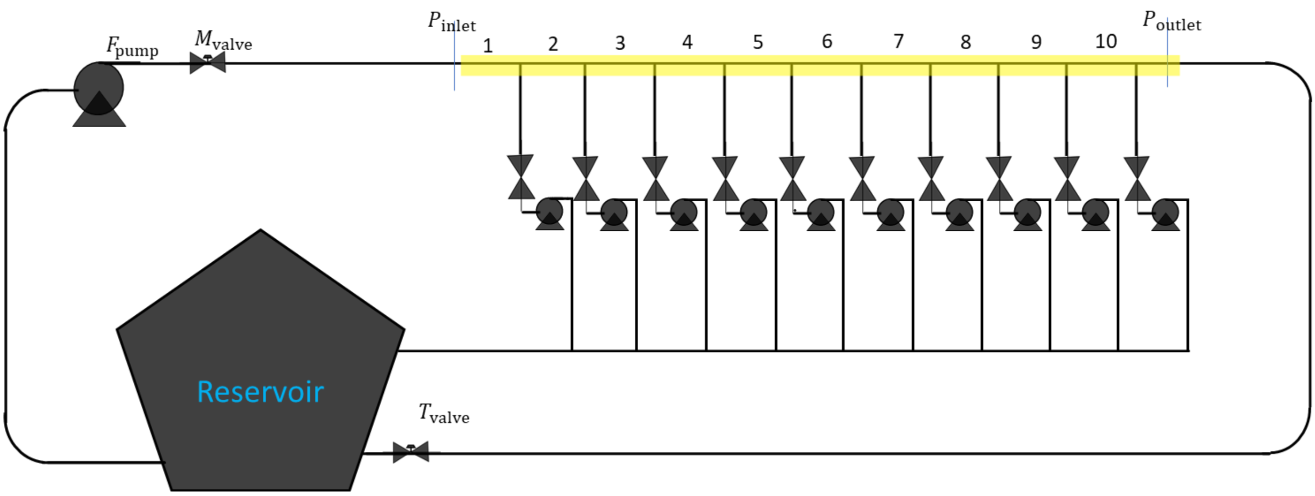


Figure 31. Simulation experimental setup

6.2.3 *Simulation software*

Several hydraulic simulation software, ranging from simple and freely downloadable ones to overly complex and awfully expensive software, are available for several industries involved in pipeline fluid transportation. Two of the very robust pipeline transport software, OLGA and PIPESIM, used by hydrocarbon exploration and production industry around the world were developed by Schlumberger[5]. A research version of PIPESIM was donated upon request, through Schlumberger UK to DMU in support of this research. PIPESIM was chosen for this research based on personal knowledge and because it is the software used by an international oil company where I gained three decades of petroleum engineering experience. Alternative fluid simulations software in a ranked order are: Surfer, Aspen HYSYS, myQuorum, CHEMCAD, PIPEPHASE, Petro-SIM, ATMOS Simulation Suite, Studio 5000 (Anon., n.d.).

6.2.4 *Pipesim solver software*

The PIPESIM software is a multiphase flow simulator designed to accurately replicate and digitally connect oil field facilities (subsurface reservoirs, wells, flowlines, flowstations, and export terminals). It can be used as a design tool for the sizing of transport processes like flowlines, pipelines and processing facilities like flowstation and central processing facilities (CPF) during field development, or redevelopment design process. PIPESIM models can also be used to design and overcome fluid flow challenges and optimize production. The details of the governing basic fluid flow equations are discussed in detail in section 8.4 on Volume, pipe diameter, leak rate effect on pressure gradient method which yields:

$$V = \frac{\pi r^4}{8\mu}\frac{\Delta P}{L}$$

which is a form of Darcy law for single phase fluid in a pipe of radius r which states that

$$q = -\frac{kA}{\mu}\frac{dp}{dx}$$

where V and q are rate of flow in the direction x and A is flow area.

[5] Schlumberger is an EP services company and specialises in the provision of technologies for reservoir characterization, drilling, production, and processing. Available at https://www.slb.com/

The Darcy law is the basic equation in hydrocarbon exploitation and transportation which was derived from a combination of mass conservation and momentum conservation equations. Several proprietary software have been designed and used in finite element analysis to solve the Darcy equation for multiphase flows using well documented two-phase correlations. Multiphase correlations depend on flow regimes and gas phases of the composition flown and are used to generate most representative conditions for the systems being solved. PIPESIM is designed for production optimization from reservoir up to the well head and from the well head through to production terminal. The main use of multiphase correlations is in the estimation of pressure drop within the tubing. Some of the well-established multiphase flow correlations used in the oil industry and their respective publication dates (El-Moniem Aly, 2016) include Poettmann & Carpenter (1952), Gilbert (1954), Duns & Ros (1961), Fancher & Brown (1963), Hagedorn & Brown (1963), Orkiszewski (1967), Aziz & Govier (1972), Beggs & Brill (1973), Cornish (1973), Gray (1978), Minami & Brill (1987), Ansari et al (1994) and Chikshi et al (1996). The applicable multiphase correlation depends on flow regime which can be wavy, annular, dispersed, froth, bubbly, slug, plug or stratified and these regimes on their own depend on crude flow rate, pressure and PVT properties of the crude.

Crude transport, as discussed in this thesis, involves the pumping of stabilised crude from flowstations to the terminal hence the constraints for stabilized fluid evacuation includes the injection rates and pressures at several flowstations. Other constraints would be the rate of flow to ensure that fluid segregation do not occur at low rates and pipeline erosion due not occur at high pump rates. But these are design parameters of any existing pipeline and hence not subject for this research which is focussed on crude evacuation during the *operate* phase. Also, fluid transport from flowstations to the export terminal involves the transport of stabilised crude which is a single fluid transport process. Notwithstanding that PIPESIM is equipped with the several multiphase correlations available in the EP industry, the use of any of these correlations is not applied in this study because crude evacuation involves the transport of single-phase stabilised crude. Only characteristic pump curves at respective injection points are applied.

Schlumberger supplies the hydrocarbon EP industry's most comprehensive range of products and services, from exploration through production, and integrated pore-to-pipeline solutions that optimize hydrocarbon recovery to deliver reservoir performance sustainably. The closest competitor to Schlumberger in the supply of similar range of oil services products is Halliburton. Halliburton[6] company is an American multinational corporation, employs approximately 55,000 (Schlumberger employs about 110,000 people) and had a revenue of 24 billion USD in 2018 (Schlumberger had a revenue of 32.82 billion USD in 2018). In terms of size[7] and return on investment Schlumberger, with a 2020 income of $10.5b for 2020 is comparable to ExxonMobil with net income of $14.3b for 2019.

Some of the optimisation success stories of Pipesim as documented by Schlumbeger include:

- PIPESIM Simulator Increases Incremental Gas Production in Mature field by 10% in Ukraine (Schlumberger, 2020).
- Staatsolie Optimizes Pipeline Network Management with PIPESIM Software, Suriname (Schlumberger, 2013b).
- AMAPETCO Optimizes Subsea Flow Assurance with PIPESIM Modelling, Egypt (Schlumberger, 2013a).
- Severneftegaz prom Reduces Operating Expenses by Using PIPESIM Software, Russia (Schlumberger, 2011).

[6] https://en.wikipedia.org/wiki/Halliburton
[7] https://craft.co/schlumberger/competitors

PIPESIM, according to Schlumberger, is based on Basic Open-source Mixed INteger (BONMIN) framework and applied on Mixed Integer Non-Linear Program (MINLM)[8] MINLPs, which arise in many real-world applications, are optimisation problems where some of the variables are constrained to take integer values and the objective function and feasible region of the problem are described by non-linear functions. (Shammari, 2019)

This research involves the modelling of the pumping of stabilised crude and so only verified the validity of results from PIPESIM through an operational workflow used in subsurface engineering modelling. This involves the regeneration of some input data or some midpoint data from software output result. E.g., if a geological model of a reservoir is created, from any given software, based on logs from some wells, we can test the model calibration by generating some pseudo logs from the created geological model near some well location and compare such pseudo logs with actual log input. A good match between the pseudo log and the actual log is a validation of the modelling software whose modelling proprietary routines are not usually openly available nor evaluated on case-by-case basis. This process was used in the testing of the models created in PIPESIM through the recalculation of the live crude viscosity of evacuated wells from the PIPESIM output results from figure 46. This result was used as a confirmation of the PIPESIM software whose detailed coding architecture is proprietary but with industry wide acknowledged capability. Major organisations in the EP industry have a highly rated and proprietary routine for certification of software and PIPESIM is used by these EP companies around the world who have certified the use of PIPESIM in their organisations.

[8] PIPESIM network optimizer, webinair, Jun 24 2019 https://www.software.slb.com/products/pipesim

6.3 Chapter summary

The originally recommended concept of using pre-leak data prognostic model for smart operations analysis method was argued as unworkable due to data paucity hence this necessitated a revisit of post-leak diagnostic data model for smart operations analysis method. Even this post-leak diagnostic data processing methodology requires some data which currently are not available to the required intensity hence necessitating some further research for the generation of the required data. The use of computer simulation, instead of rig-based laboratory experiments, was chosen based on cost, time requirement, and ability to replicate actual pipeline.

PIPESIM flow simulation software from Schlumberger was chosen based on personal knowledge and peer reviews. Request was made to Schlumberger UK and a research version of the software was donated to DMU. Pipesim is widely used around the world. It is a proprietary software based on Basic Open-source Mixed INteger (BONMIN) framework and applied on Mixed Integer Non-Linear Program (MINLM), but the robustness of the software was evaluated based on recalculation of input variable from basic flow equation based on output results from the software. This result was used as a confirmation of the PIPESIM software whose detailed coding architecture is proprietary but with industry wide acknowledged capability.

7 PIPELINE SECTIONAL LEAK EXPERIMENTS

7.1 Introduction

Crude oil transport involves the pumping of stabilised crude from flowstations through delivery lines to trunklines, or directly from flowstations to trunklines for delivery to their respective export terminals or inland crude refineries. At export terminals, crude is processed to export quality and sold to ocean tankers for export while processed crude at inland refineries are redistributed through refined product lines. Both the delivery lines and trunklines are major live arteries in the EP process as crude are continuously transported through them with very minimal interruptions.

The literature review has highlighted the usefulness of Hydraulic flow simulation for accurate well flow modelling and performance prediction. It has also been conceptually advocated on section 3.4.4 on Smart fields operation page 76 that, if we could model the production performance of a pipeline then we could also use such a model to determine leak or crude theft points and possibly estimate the rate of leak or theft. Two study base models, of a major trunkline and a commingling well delivery line, were therefore created and used together with other conceptual experiments, to test this concept. The trunkline experiments are for reprocessing of collected data for the generation of intermediate trunkline pressure measurements for the testing of the research hypothesis. The delivery line evacuation experiments were simulated to generate data for testing the relationship between flowrate and leak rate on one hand and pipeline transmission pressure on the other hand. Some of the delivery line experiment involves variation of the base model data for evaluating sensitivities of key flow parameters.

7.2 Basis for simulation setup

An initial review of some installed trunklines in the Niger delta shows that:

- A major evacuation trunkline could be as long as 160km and acts as a trunk, or backbone, unto which several flowlines and delivery lines spike fluids at intervals for transmission to the export terminal. The diameter of these trunklines could, based on volume of crude being evacuated, vary from 12 inches up to 36 inches as more crude are injected.
- The crude evacuation energy is provided by the respective flowstation pumps that are sized such that preceding upstream pumps at each spiking point operate at slightly higher pressures needed to overcome gravity and viscous forces upstream of downstream pumps while subsequent downstream pumps act as booster pumps at each injection point. As a result of this configuration, the pipeline evacuation network is a constrained open system with pressures decreasing from upstream towards the terminal where crude is discharged at a pre-set pressure that is higher than atmospheric pressure.
- The crude discharge pressure at the export terminal is maintained at some pre-set point in other to maintain some form of flow regime throughout the length of the trunkline. The evacuation or crude transport process therefore involves filling the trunkline with crude and pressuring the pipe to the pre-set terminal discharge pressure before the first crude is received at the terminal. As a result of this, the discharge point pressure at the terminal may not be suitable for use as a pressure monitoring point. A suitable set of pressure points, upstream of the terminal discharge point, should therefore be chosen for monitoring the effect of crude theft on transmission pressures.

Available pipeline configuration and production data from one major Niger Delta trunkline were used to construct a pipeline evacuation model in PIPESIM. The created model is a 75km pipeline with three sections: 18.96km, 20-inch diameter line between FS1 and BC_MF; 9.44km, 24-inch diameter line between BC_MF and FS4_MF and 45.87km, 24-inch line between FS4_MF and Terminal. This Trunkline was also configured to receive additional crude oil from two other sources at BC MF as shown in Figure 32 below. The first flowstation supplies its crude via a delivery line to the modelled trunkline case which delivers some 105,000 bpd to an export terminal.

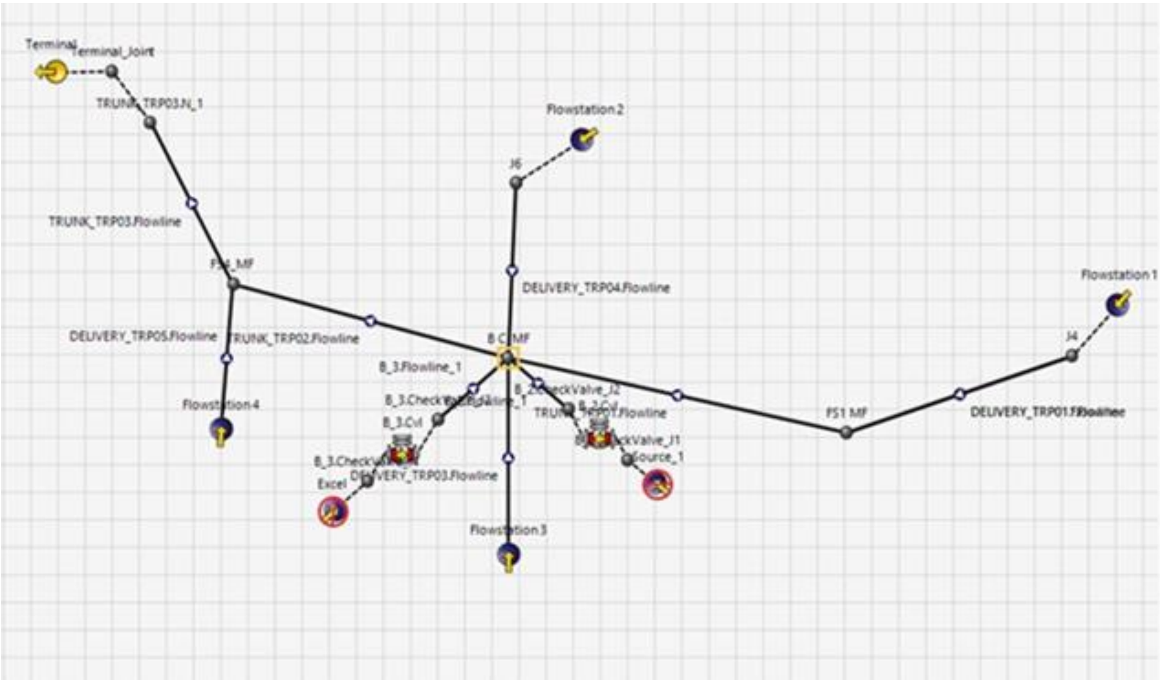


Figure 32. Trunkline case simulation experiment

For ease of analysis, one node is added respectively to each trunkline section. Three flow conduits with check valves are attached at these additional nodes for use in simulating hot tapping and crude theft operations as shown in figure 33.

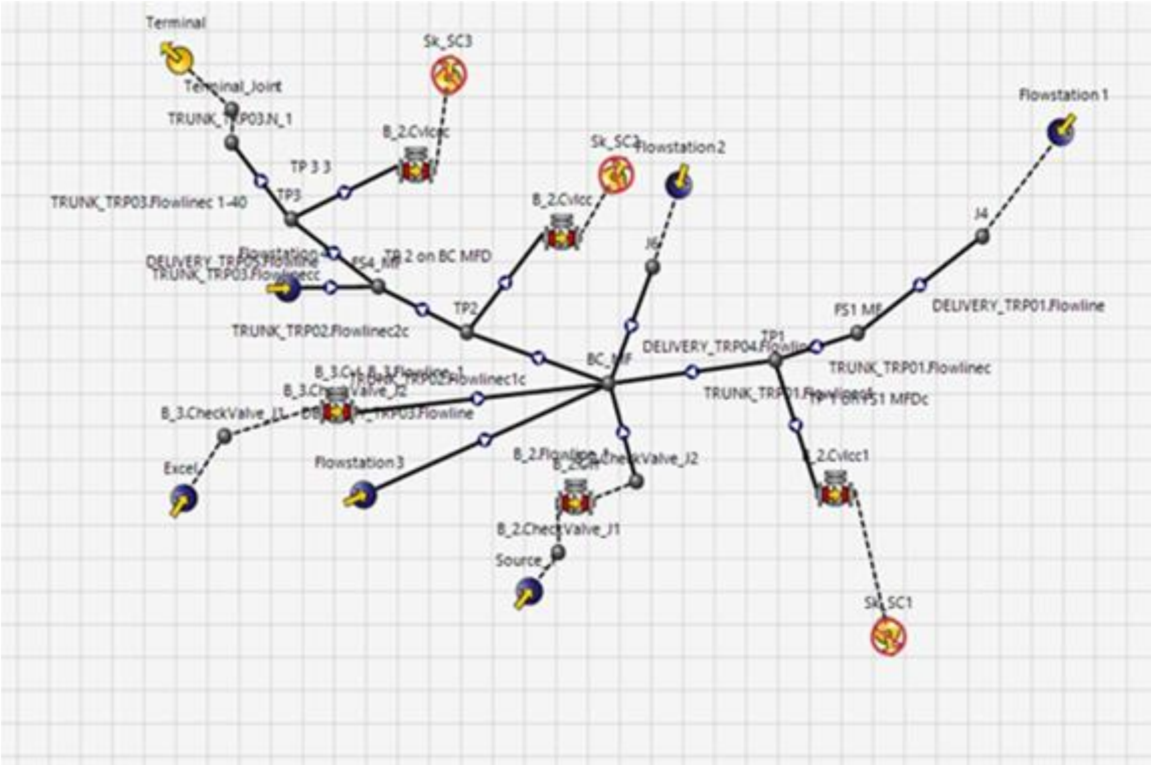


Figure 33. Trunkline case simulation experiment with crude theft tapping points.

All the attached crude tapping points were isolated using installed check valves after which crude evacuation exercises were simulated to generate pressure responses as required. Figure 34 shows the pressure response without leak and this result will be used as a baseline for all simulation exercise on this trunkline for the evaluation of pressure responses due to leak.

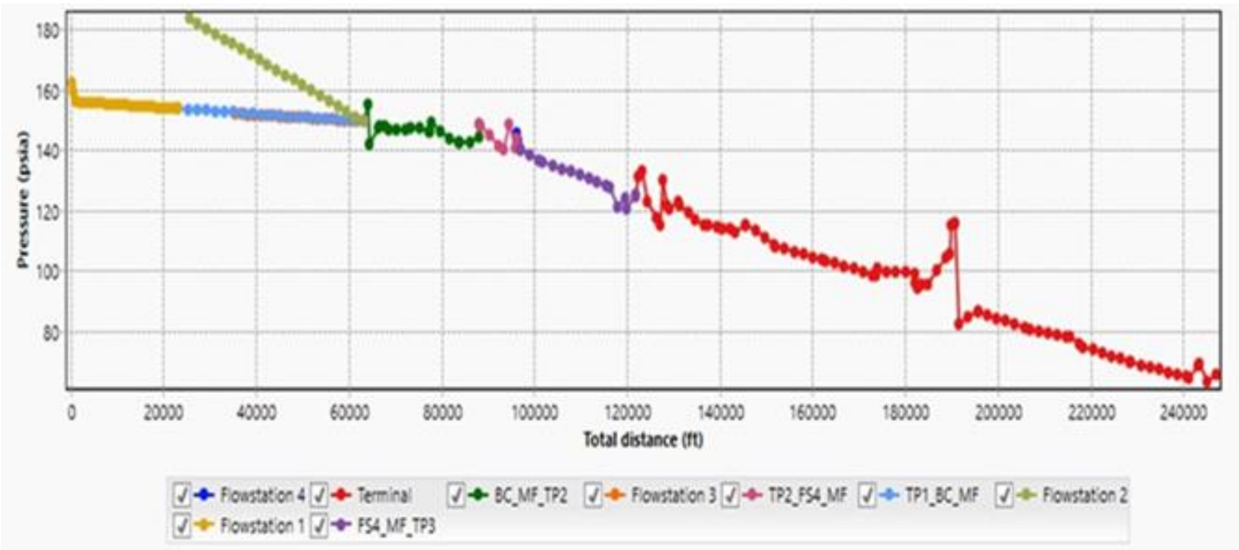


Figure 34. Trunkline case pressure profile without a leak

7.3 Single sectional leak experiment

This sectional leak investigation aims at trying to distinguish leaks from any of the three sections of the case pipeline being investigated. The experimental setup is as shown in figure 33. Single leaks of 5,000 bpd, 10,000 bpd, 15,000 bpd, and 20,000 bpd were respectively simulated at TP1, TP2 and TP3 and the effects of these simulated leak on nodal pressures at TP1, BC_MF, TP2, FS4_MF, and TP3 were recorded. TP1, TP2 and TP3 represent simulated theft (or tap) point 1, 2 and 3 respectively. FS4_MF is the manifold for the injection of fluid from flowstation 4 while BC_MF is a central major manifold.

The required leak simulation is achieved by activating the desired leak point (TP1, TP2, or TP3) and opening the check valve such that the desired leak or theft volume flowrate can flow. This leak effect could also be achieved by creating a pressure differential at the desired leak points or by installing chokes at each tapping point and opening such chokes as desired to get the required crude rate to flow in the required leak direction.

The pressure responses at all monitoring nodes during the simulated crude evacuation operation were downloaded and documented after each simulation. These respective records were then used to generate pressure differential plots as shown in figures 35, 36 and 37 respectively for leaks at TP1, TP2 and TP3, respectively. The pressure differential for the respective leak simulation is the difference between the operating pressure at any given point when there is no leak and the respective pressures during a corresponding leak.

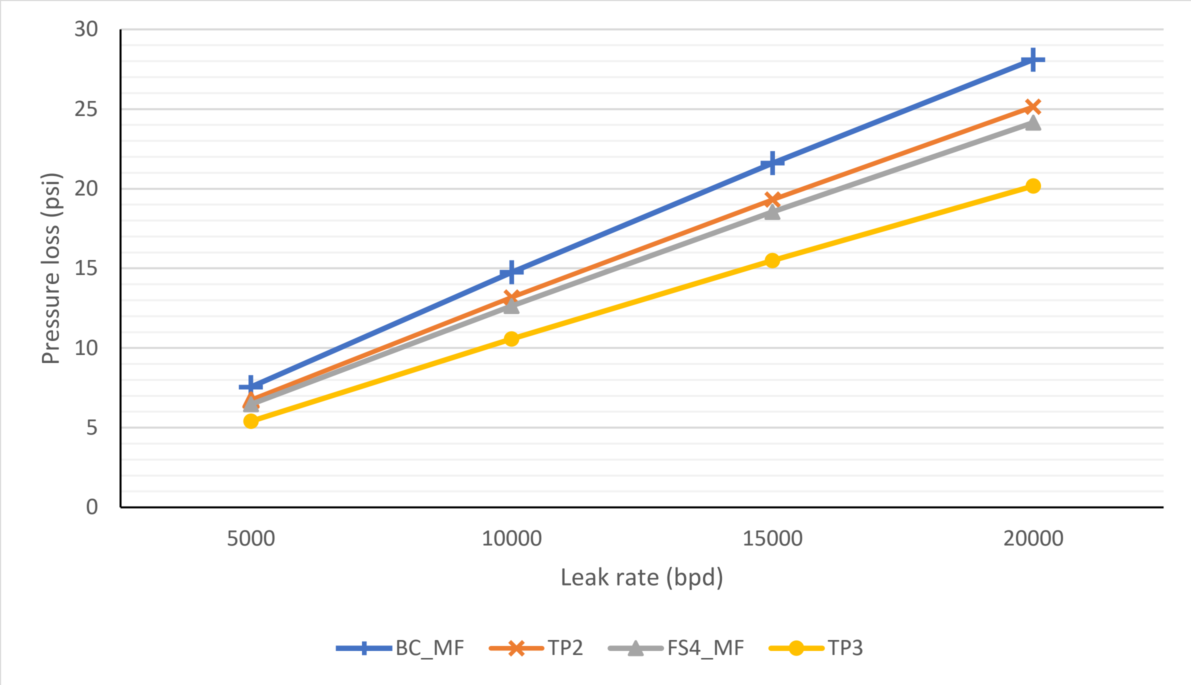


Figure 35. Pressure loss (psi) due to leak at TP1

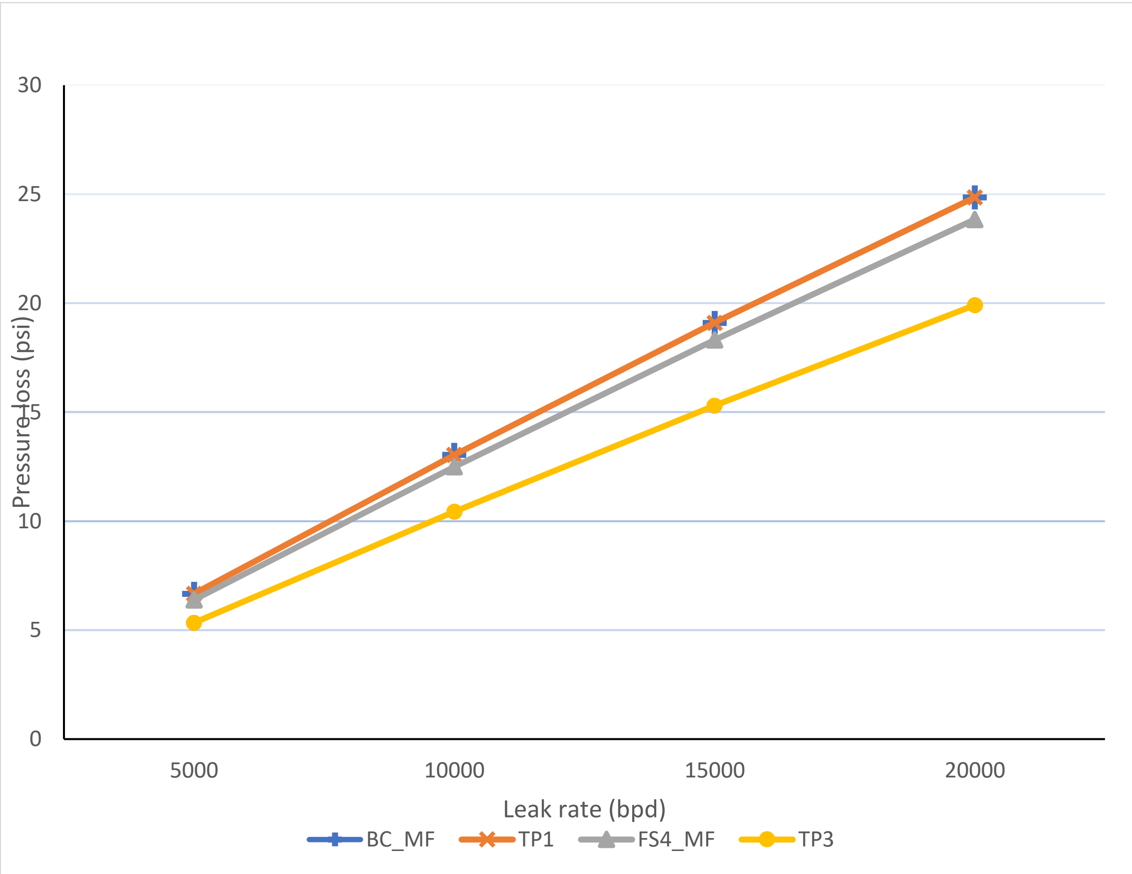


Figure 36. Pressure loss (psi) due to leak at TP2

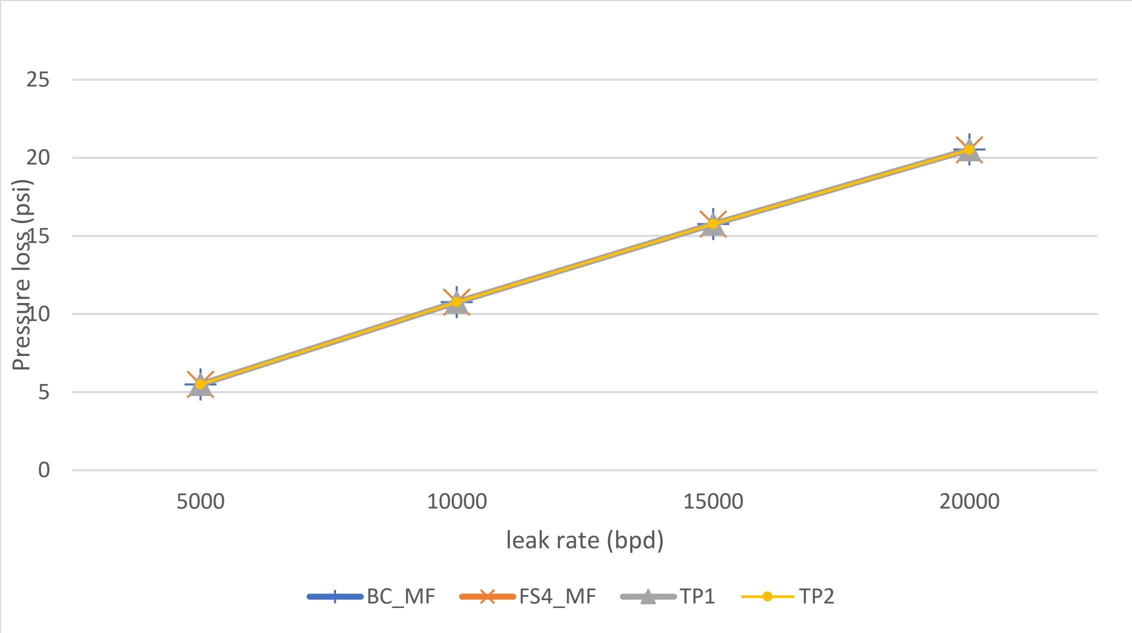


Figure 37. Pressure loss (psi) due to leak at TP3

7.4 Simulation result discussion

One of the easily discernible findings from these experiments is that the farther upstream the leak point is the wider the pressure differential is between a no-leak situation and a situation where crude oil is leaking or stolen. This pressure differential narrows as leaks point gets closer to the export terminal point. Another finding is that the pressure differential is sensitive to the position of monitoring point with respect to the point of leak. As can be seen from figure 35 and 36 any set of pressure monitoring point upstream to the point of leak would yield the same pressure differential. Figure 37 for example shows that the pressure differential for all the four monitoring points plot exactly on the same line. This could be explained based on the leak position which is downstream of the four monitoring points. So long as the system is concerned all monitoring points are in steady state until the leak at TP3 and so respond in the same way. This is a shortcoming for using pressure differentials and would be addressed during future experiments.

These experiments have therefore demonstrated that crude oil theft could be monitored from pressure measurements only. These experiments have also proven that you really do not need to know the pressure values at every position on the trunk line in other to define flow or monitor leak. Having measurements at just a few evenly spaced positions in each trunkline could just be enough to monitor leak on that trunkline. This supports the argument that the use of external Fibre optic sensing, page 80 which is prone to vandalism is not really needed throughout the length of the pipeline as a way of monitoring leak. However not having enough monitoring points could also be a handicap because even though we could observe that a leak may have occurred we may not be able to exactly estimate where the leak is. This same situation exists if the leak is downstream of the last pressure monitoring point based on current experimental findings. The question then is what is the recommended spacing between data acquisition points. Three measurements over a length of 100km is not acceptable and as explained the spacing between data acquisition point determines the accuracy of measurements and the time to response. A near perfect (100%) accuracy in leak point determination was achieved in this thesis but a 93.44% average leak rate prediction accuracy was demonstrated based on the proposed smart process for pipeline integrity monitoring. The spacing between monitoring points (5km or 10km) would therefore have some effect on the leak rate prediction accuracy. But as explained in section 9.6.3 on Pipeline digital information data acquisition system page 201, there is a security risk of vandalism of some of these data acquisition infrastructure, so there must be a trade-off between the required accuracy and the increase in operating expenditure due to manning of additional data acquisition infrastructure points. Based on the forgoing, considering that 24-hour manning of at least two persons per shift everyday it seems that such data acquisition infrastructure should be recommended every 10 or 15km to avoid some creep in operating cost for such pipelines.

The next finding relates to the minimum leak that one can detect from the proposed smart process from this research. As shown in figure 35, 36 and 37 a leak rate of 5000 bpd from a 105,000-bpd evacuation system would, depending on the position of the sensor give rise to a pressure differential of 5 – 7 psi. This implies that for this operating Niger delta pipeline a 5000-bpd leak at the far end pressure sensor would lead to a 5psi pressure differential. These results tend to suggest that 1000bpd constant leak rate could yield 1psi pressure differential, but can we really measure 1 psi in a Kerotex analogue pressure gauge? Is it possible that a crude oil thief would invest in a tapping operation just to steal 1000 barrels per day which translates to 30 gallons per minute? In section 3.4.1 on Fiscal reconciliation page 66 it was stated that 95% RF (5% leak) for a major truckline is not investigated as this could be due to different meter accuracies, shrinkage losses due to temperature variations, liberation of dissolved gasses, or due to leaks. The research hypothesis is focussed on steady state so in effect we are monitoring trends rather than instantaneous values. The question therefore is what differential pressure change is worth investigating as a theft point? Every differential pressure above 5psi is worth investigating for crude theft while pressures less than 5 psi can be acknowledged as an acceptable reconciliation due to the reasons provided above for this particular pipeline.

The pressure differential due to leak is proportional to the rate of leak, hence with a few representative experiments one can create several relationships between leak rate and pressure differentials which could be monitored at chosen points and used to predict leak point and rate. A new set of experiments were therefore conducted to confirm this finding.

7.5 Predicting leak using pressure differential

Differential pressure readings at critical pipelines can be designed and used to monitor the given pipeline integrity as a dashboard. Every automotive, for example, has dashboard that is equipped with instruments for measuring parameters like temperature and pressure sensors of critical safety automotive components and depending on such readings warn drivers of abnormal vehicle situations which needs investigation. Similarly, since it is proven that leak during pipeline evacuation could be detected through pressure measurements alone and just an evenly spaced pressure monitoring points is sufficient for leak detection, one could design a new process for leak or crude theft detection through pressure monitoring for accurate prediction of leak point and rate. A new set of experiments were therefore designed to predict leak based on pressure measurements alone.

Figure 38 was created based on figure 36 data for the purpose of predicting single point leak around TP2 through the monitoring of differential pressures from a pair of points on either side of the leak.

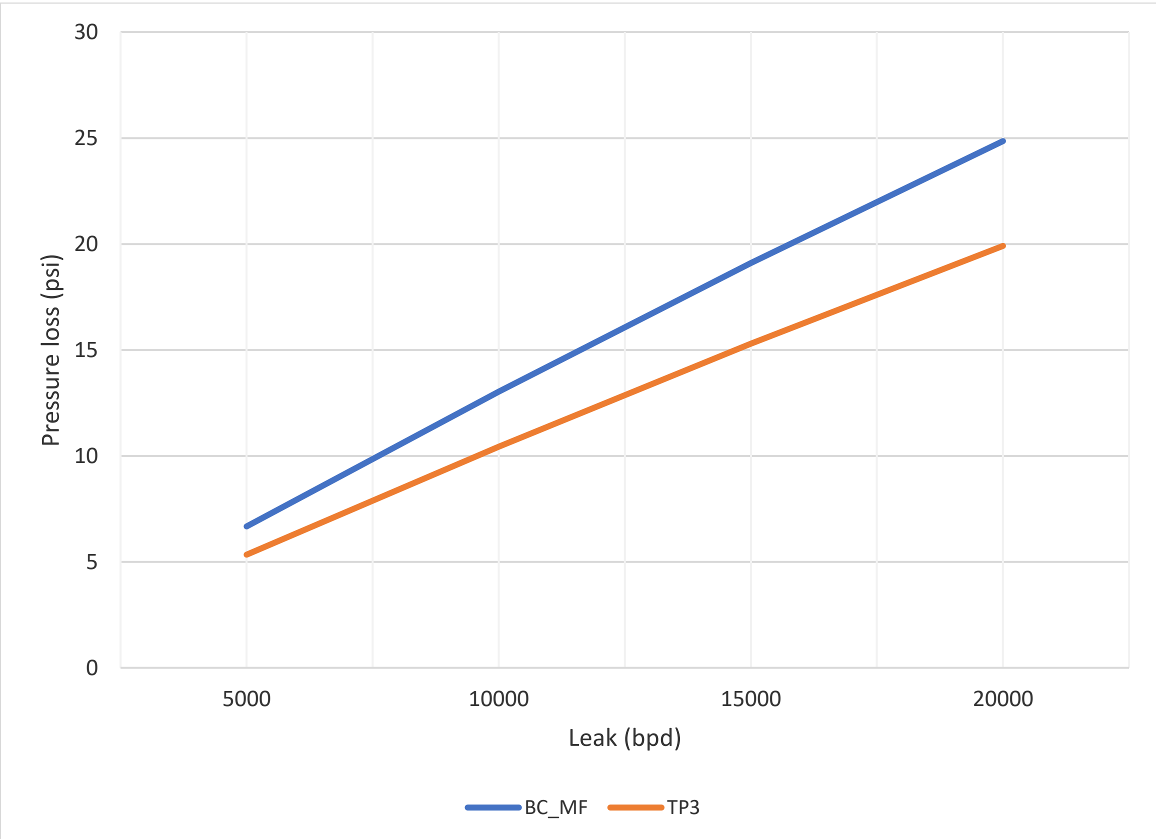


Figure 38. TP2 leak monitoring chart from two pressure monitoring points

Frome Figure 38 we can deduce that:

- If a pressure differential of 10psi (139.45 psi actual reading) and 7.5 psi (117.52 psi actual reading) are recorded at BC_MF and TP3 nodes respectively, it means that 7500 bpd is leaking or stolen around TP2.
- If a pressure differential of approximately16 psi (133.45 psi actual reading) and 12.5 psi (112.52 psi actual reading) are recorded at BC_MF and TP3 nodes respectively, it means that 12500 bpd is leaking or stolen around TP2.
- If pressure differential of 22 psi (127.45 psi actual reading) and 17.5 psi (107.52 psi actual reading) are recorded at BC_MF and TP3 nodes respectively, it means that 17500 bpd is leaking or stolen around TP2.

Three experiments were executed to verify these predictions and the results which are in perfect agreement are as shown in table 2 below.

Table 2. Simulation pressure results for TP2 leaks predicted from figure 38.

Monitoring point	Pressure due to 7500 bpd leak (psi)	Pressure due to 12500 bpd leak (psi)	Pressure due to 17500 bpd leak (psi)
BC_MF	139.56	133.34	127.43
TP3	117.10	112.12	107.39

7.6 Discussion

Table 2 results are conclusive and shows that with only a few sets of experimental results using representative monitoring points in this pipeline one could generate infinite realisation of leak failures in the same pipeline that could be used to determine leak in any of the three sections of the given pipeline through interpolation and extrapolation. The above experiment also demonstrates that leaks can be detected through pressure monitoring alone. Without any leak the evacuation pressure plot in any pipeline will be a straight line which obeys the fluid flow equations, hence any deviation from the expected normal situation could be used to detect leak. In a complex network therefore, one could use pressure trending to self-calibrate any pipeline system for use in the determination of potential leak sources. Once calibrated a knowledge-based system could be developed such that future leak data can be used to train the knowledge system to recognise leak. This set of experiments have shown that the leak being investigated must be bound by one pressure monitoring point on each side and where such condition is met, we can use the pressure differential alone to determine leak point and leak rate in a single leak situation. Our capability to extend this finding to a universal pipeline integrity monitoring process and the possibility of removing the conditional clause, for use of pressure differentials, was studied further.

7.7 Chapter summary

The engineering basis for using crude oil evacuation modelling for predicting leaks has been introduced and verified using PIPESIM. A set of experiments have been simulated and the output data corresponding to several input data has been investigated and recorded. The output data were analysed to see if through the knowledge of pressure variations at control points alone we could determine at what point the crude oil leak happened as well as the leak rate. Observed results were conditionally encouraging and shows that with only a few sets of experimental results in any pipeline one can generate infinite realisation of leak failures in the same pipeline that could be used to determine leak point and leak rate in a single leak situation.

The optimum spacing between data acquisition points depends on the likelihood of the vandalism of these data acquisition infrastructure. This implies that there must be a trade-off between the required leak rate prediction accuracy and the increase in operating expenditure due to manning of these additional data acquisition infrastructure. Based on the forgoing, considering that 24-hour manning of at least two persons per shift every day at these data acquisition points it seems that such data acquisition infrastructure should be recommended every 10 or 15km to avoid some creep in operating cost for such pipelines.

Also, the minimum pressure detection that one could target with the proposed smart process was discussed and coincidentally could be taken as that which translates to 5% leak. It is therefore recommended that for a pipeline evacuating 100,000 bpd crude, every differential pressure above 5psi is worth investigating for crude theft while pressures less than 5 psi can be acknowledged as an acceptable reconciliation due to operational reasons rather than leak. Just like appropriate pressure gauges are mounted on pipelines depending on the pressure regime of such pipelines, the limit of pressure monitoring during fluid evacuation would depend on the volume evacuated, and pressure regime of such pipeline. It is recommended that the minimum pressure differential worth monitoring would be that relating to 0.95 RF.

This case study was conducted on a particular pipeline so the results therefrom typically should apply to this pipeline. It demonstrates that for a given pipeline with evenly spaced pressure measurement opportunities, we could use the pressure variations from these pressure measurement points to determine the point of crude leak or theft from any section of the trunkline. This results conditionally support this thesis hypothesis and would be further studied for universal application.

8 BASIS FOR USE OF PRESSURE GRADIENTS IN LEAK EXPERIMENTS

8.1 Introduction

It has been shown that monitoring of pipeline pressures at a few evenly spaced pressure nodes in a pipeline is just sufficient for leak detection. This chapter attempts to validate the use of pressure gradient, which is based on pressure differential, for leak detection. Some additional experiments were therefore executed to fully quantify the relationship between known influencing parameters like flow rate and conduit size on pressure gradient during crude evacuation process.

The purpose of this chapter is to highlight the basic theory for fluid evacuation using Navier stokes equation and simulate some experiments for the generation of intermediate transmission pressure output results to the required intensity for the testing of research hypothesis.

8.2 Pressure gradient method for leak detection

The crude evacuation pipeline configuration is determined by the location of discharge terminal in relation to the flowstations being evacuated, and the terrain in between. The properties of the crude being transported also vary and influence pump energy selection. As documented in Reflexivity, positionality and research mind map this research is approached from the perspective of introducing subsurface engineering best practices to pipeline transport systems. Why should an operator attach cameras to specialised helicopters for daily flights over facilities as a way of improving pipeline asset surveillance operations as is done in Niger delta (Shell Nigeria, 2020). This daily helicopter overflies are risky, expensive, damaging to the environment through continuous emission of greenhouse gases, and unacceptable as cost discipline through reduction in cost logistics should be championed as done in other jurisdictions (Oil & Gas Authority, 2017).

The crude evacuation process from the subsurface reservoir to the export terminal involves reservoir inflow from the reservoir to the well bore, thereafter there is a vertical fluid flow from the wellbore to the well head and thereafter we have a horizontal fluid flow from flow station to the terminal. As a result, and as discussed in Subsurface Hydraulic flow simulation, some of the PWR in petroleum engineering would be investigated in this pipeline transport research.

Pressure gradients have been used in subsurface reservoir engineering studies to show transition planes between reservoir immiscible fluids of gas, oil, and water. This is especially true in newly discovered hydrocarbon accumulations where the luxury of using electric logs, for fear of being stuck in uncased holes, is not considered as a safe data gathering option. As part of exploration drilling into these reservoirs, pressure samples therefore are recorded at prognosticated gas, oil and water sections of the reservoir being explored. The pressures corresponding to these pressure samples are then used in generating gradient plots at respective reservoir sections for the estimation of gas-oil contacts and oil-water contacts as shown in figure 39 .

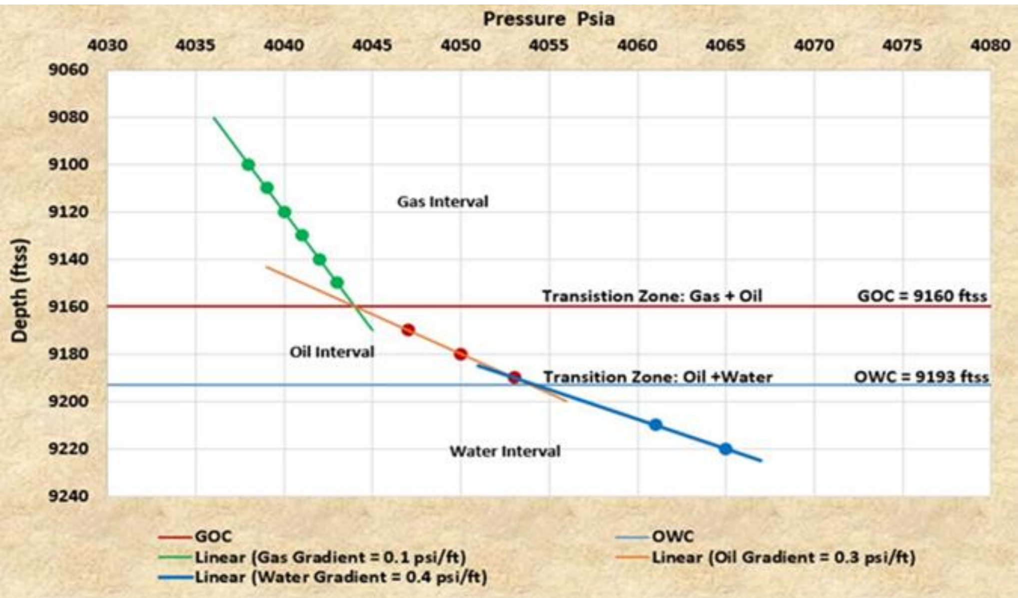


Figure 39. Pressure gradient plot for reservoir fluid contact determination

Virgin reservoirs found during hydrocarbon exploration are good examples of a closed hydraulic system where gas, oil and water are in equilibrium, hence the use of pressure gradient plot to determine fluid interface planes. Also, in reservoir engineering, having known the original pressure gradient and size of reservoir we could use the current reservoir pressure to estimate how much of crude must have been produced. This is a practice worth replication in this research, where having known the original evacuation pipeline pressure gradient without a leak, one could use the new pressure gradient to estimate how much fluid is leaking or being stolen. This is a similar process being followed in resolving trade disputes involving a subsurface hydrocarbon reservoir straddling two acreages being produced by different operators, sometimes with independent jurisdictions, where there is an over reliance on the reservoir pressure trends to determine the total volume of hydrocarbon produced by the combined operators.

Even though the pipeline crude evacuation process is not a fully closed system, one could ignore some energy losses and assume that the pressure gradient is constant as conceptualised in the Basis for design, page 138 such that any deviation from the anticipated pressures could be used to determine the leak rate. For any crude evacuation to take place there must be a pressure gradient from the hydraulic source to the hydraulic sink and experiments so far has shown that in a non-leaking system the pressure gradient is constant. However, the onset of leak at any point divides the original constant gradient into two sections with different slopes. For a single leak system this change in slope is sufficient for use in leak point determination.

8.3 Single leak investigation at single point using pressure gradient method.

Additional experiments using a two well commingling study simulation was used for the study of pressure gradient changes during leaks. Model setup is as shown in Figure 40 while figure 41 and figure 42 show the evacuation pressure response without a leak and with midpoint leak, respectively. The data for the respective PIPESIM experiments are shown in Table 3 and table 4, respectively.

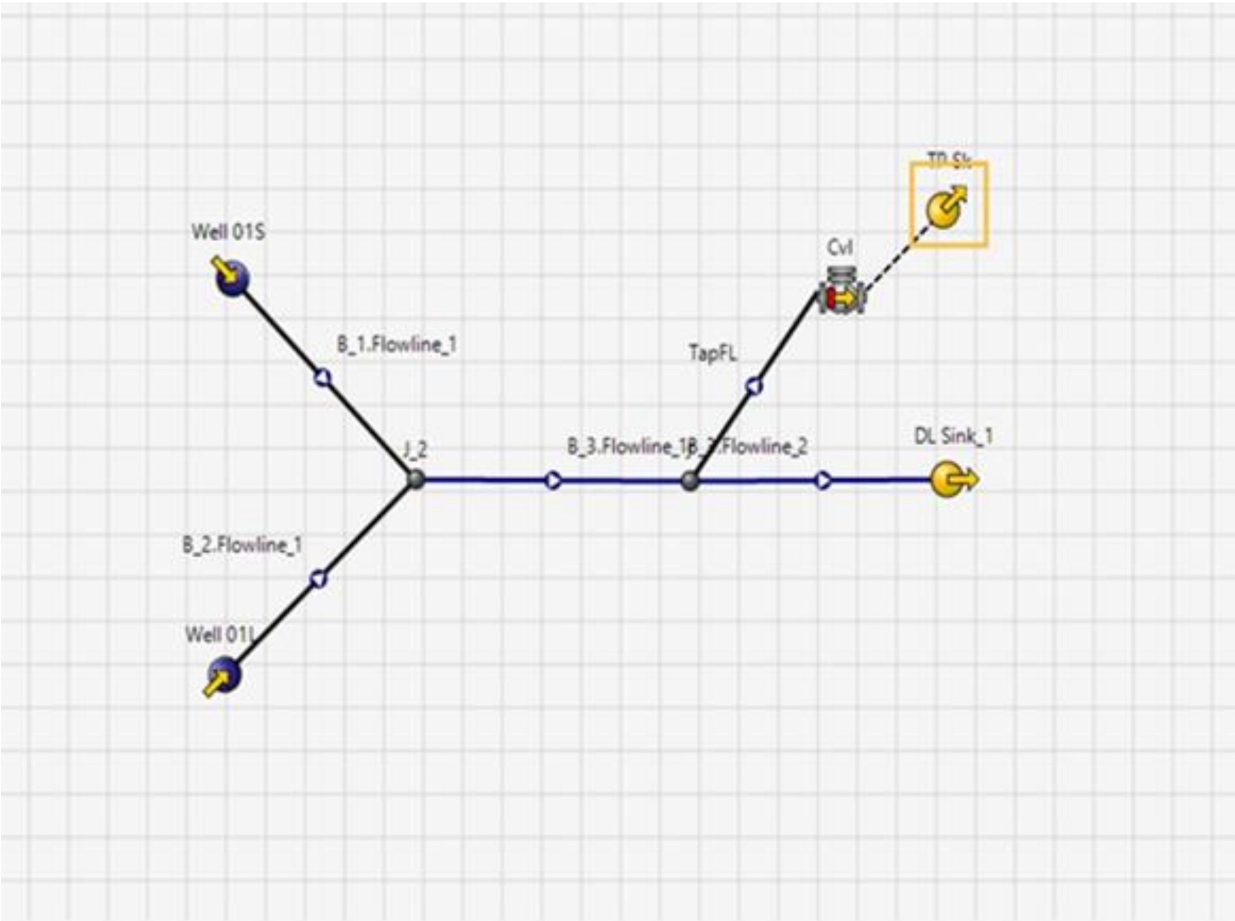


Figure 40. Single leak experimental setup

Table 3. PIPESIM output data without a leak

NAME	TYPE	Pressure psia	Temperature degF	ST Liquid Rate STB/d	ST Oil Rate STB/d	ST Water Rate STB/d	ST Gas Rate mmscf/d	ST GOR SCF/STB	ST WCUT %	FL GR mmcf/d	FL WC %
J	Junction	211.3647	76.99914	1074	1074	0	0.2829172	263.4236	0	0.01737375	0
J_2	Junction	347.4148	85.69438	1074	1074	0	0.2829172	263.4236	0	0.009588858	0
DL Sink_1	Sink	50.955	76.99997	1074	1074	0	0.2829172	263.4236	0	0.08220815	0
Well 01L	Source	351.6244	86	481	481	0	0.1423761	296	0	0.004904695	0
Well 01S	Source	347.5213	86	593	593	0	0.1405411	237	0	0.004613217	0

Table 4. PIPESIM output data with midpoint leak

NAME	TYPE	Pressure psia	Temperature degF	ST Liquid Rate STB/d	ST Oil Rate STB/d	ST Water Rate STB/d	ST Gas Rate mmscf/d	ST GOR SCF/STB	ST WCUT %	FL GR mmcf/d	FL WC %
J	Junction	162.0959	77.00023	1074	1074	0	0.2829172	263.4236	0	0.0236158	0
J_2	Junction	304.8467	85.6942	1074	1074	0	0.2829172	263.4236	0	0.01134773	0
DL Sink_1	Sink	50.955	76.99865	724	724	0	0.1907188	263.4236	0	0.05541764	0
TP Sk	Sink	19.42701	76.44487	350	350	0	0.09219834	263.4236	0	0.07186557	0
Well 01L	Source	309.1536	86	481	481	0	0.1423761	296	0	0.005765545	0
Well 01S	Source	304.9595	86	593	593	0	0.1405411	237	0	0.005486531	0

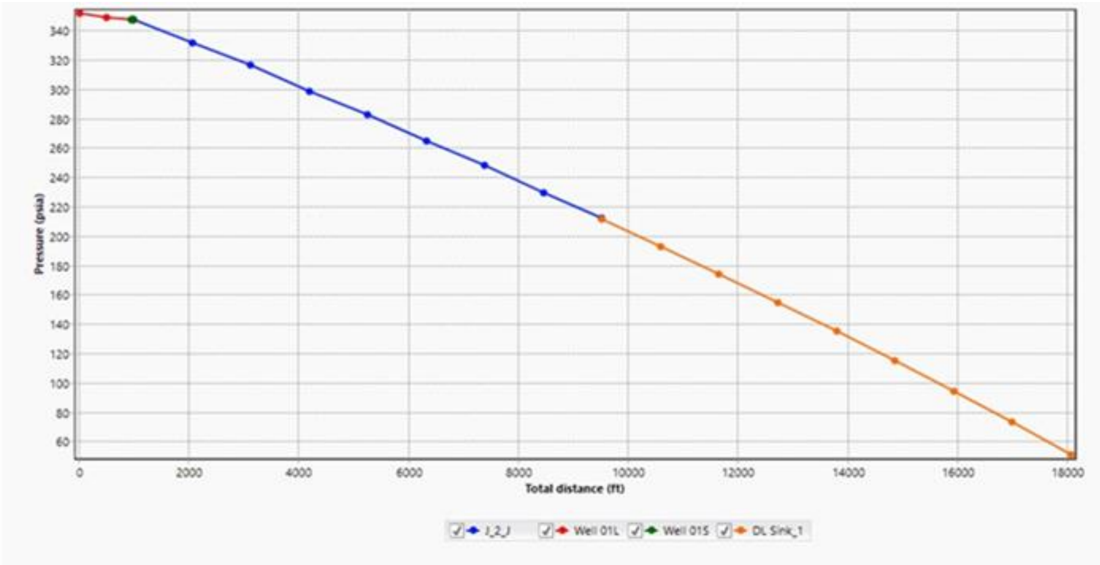


Figure 41. Evacuation pressure profile without a leak

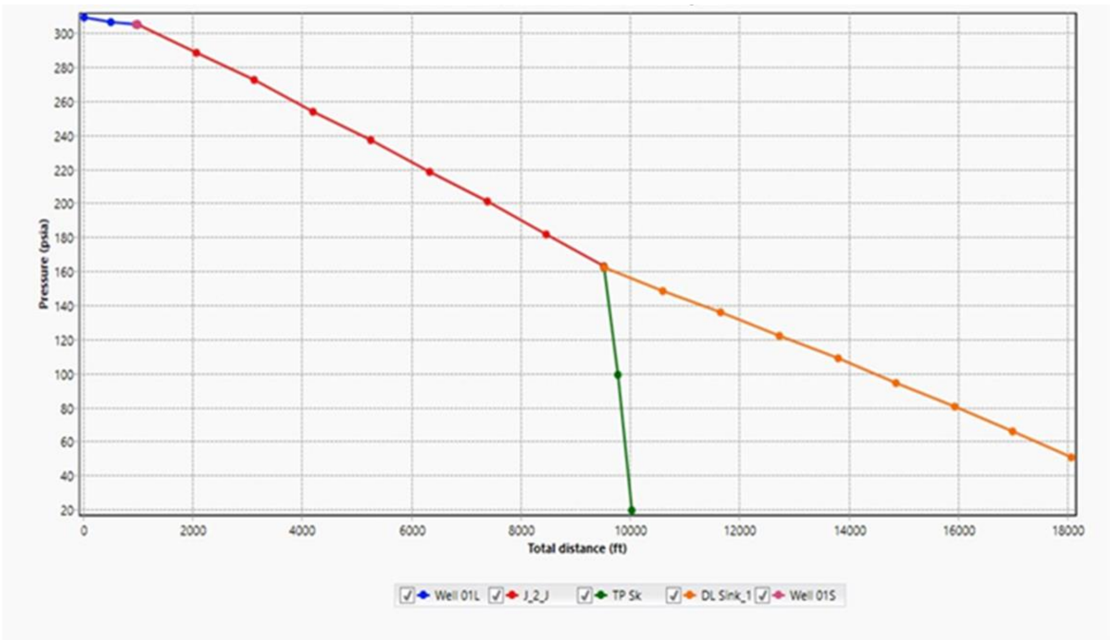


Figure 42. Evacuation pressure profile with midpoint leak

A general observation from figure 41 experimental result is that the pipeline system is not really a fully closed system where the pressure gradient is a perfect straight line. This is primarily because the pressure at both inlet and outlet are constrained, as highlighted in section 7.2on Basis for simulation setup page 145, to ensure that the pipeline is always filled with crude at every section. This therefore yields some pressure dissipation in the form of pipeline ballooning in other to achieve a fully filled pipeline before the discharge of first crude at the terminal. This ballooning or slightly pressured system causes the pressure gradient slope to deviate from a perfect straight line. The pressure performance plot from Figure 41 and Figure 42 shows that this pressure gradient slope deviation could be used to determine the point of leak.

From Figure 41, without a leak

$$\frac{\partial p}{\partial x}_{\lim_{J\_2 \to J}} = \frac{211 - 347}{8530} = -0.015943\, psi/ft$$

$$\frac{\partial p}{\partial x}_{\lim_{J \to DLSink\_1}} = \frac{51 - 211}{8530} = -0.018757\, psi/ft$$

The above calculation on the same curve demonstrates some energy dissipation due to ballooning. This error margin of -17% is a demonstration that some energy is lost by executing fluid transport in this experimental model. It is possible that in meticulously designed system such energy loss could not be as much.

From figure 42 with a midpoint leak

$$\frac{\partial p}{\partial x}_{\lim_{J\_2 \to J}} = \frac{162 - 347}{8530} = -0.02169\, psi/ft$$

$$\frac{\partial p}{\partial x}_{\lim_{J \to DLSink\_1}} = \frac{51 - 162}{8530} = -0.01301\, psi/ft$$

Unlike in Figure 41 where a -17% change in slope was explained as due to pipe ballooning, the 67% slope change in opposite direction recorded in figure 42 is due to leak which modified the steady flow at the point of leak. This intersection of two gradient lines in figure 42, as demonstrated in Pressure gradient method for leak detection page 158, is a confirmation of leak which manifests as a change in resultant pressure gradient. Many researchers have used this fact for proposing leak detection solutions, but those attempts were also based on auxiliary instrumentation using experimental rigs and some form of online sensors. This research has argued, on Frequency response function modelling page 82, that the use of intrusive volume measurement instrument is not admissible on oilfield trunklines and so will not build on such literatures that focussed on instrument-based auxiliaries. Rather some experiments were further studied for the relationship between volume flow rate and pressure gradient relationship.

8.4 Volume, pipe diameter, leak rate effect on pressure gradient method

8.4.1 *Experimental setup and results*

This leak simulation experiment is modelled on a 13km delivery line used for the evacuation of hydrocarbon flow from two wells as shown in figure 43.

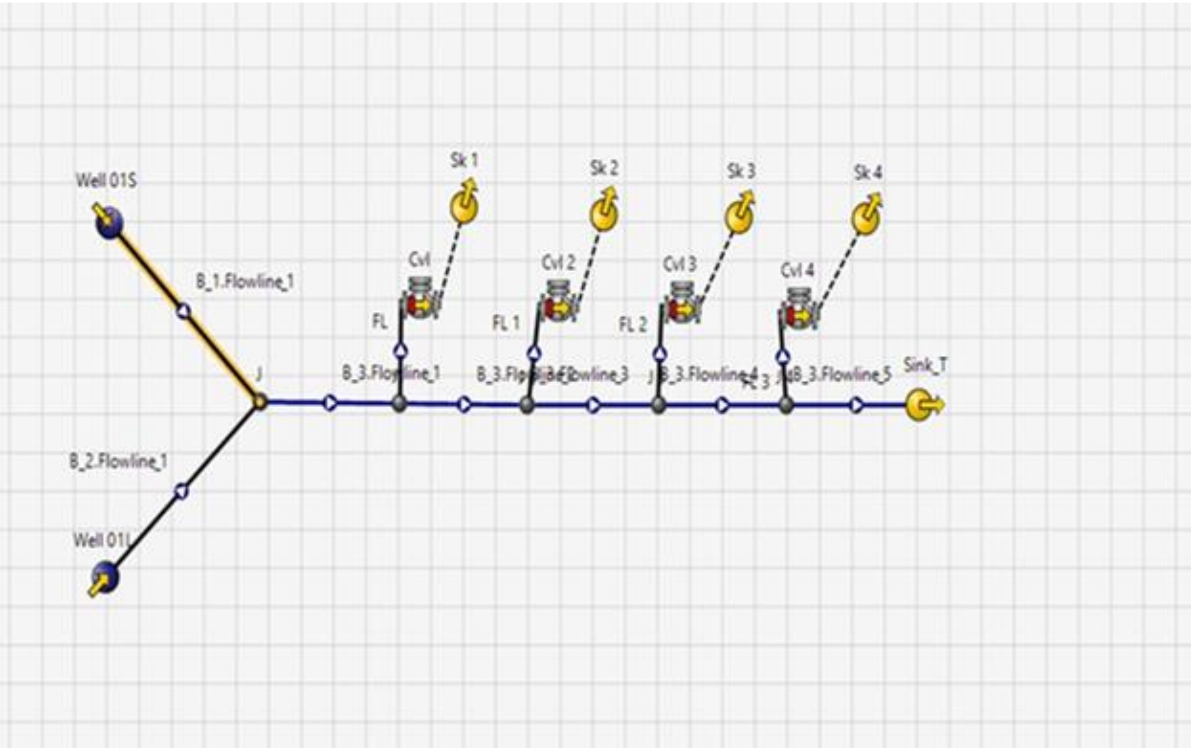


Figure 43. Pressure gradient dependency experimental setup

Four equally spaced leak points which divides the pipeline into five sections with distances of 0.2L, 0.4L, 0.6L and 0.8L respectively were attached on a 13 km delivery line for the evacuation of live crude from well01S and well01L. Leaks representing 0.95, 0.90, 0.85, 0.80, 0.75 RFs were simulated during the evacuation of 6000bpd crude oil through 6-inch pipe diameters. The respective check valves (Cv1, Cv2, Cv3 and Cv4) were installed to ensure that links to the corresponding sinks (Sk1, Sk2, Sk3 and Sk4) or theft points could be simulated.

8.4.2 *Pressure gradient response to volume*

Table 5 shows the pressure gradients in psi/ft due to simulated single leaks with their resultant RFs at the respective leak positions (TP1, TP2, TP3 and TP4) during the transportation of 6000 bpd crude while figure 44 shows a plot of table 5.

Table 5. Pressure gradient (psi/ft) response due to leak

RF	TP1	TP2	TP3	TP4
0.95	-0.01123	-0.01174	-0.01226	-0.01287
0.9	-0.01142	-0.01191	-0.0124	-0.01297
0.85	-0.01162	-0.01208	-0.01254	-0.01306
0.8	-0.01184	-0.01226	-0.01268	-0.01315
0.75	-0.01206	-0.01245	-0.01282	-0.01325

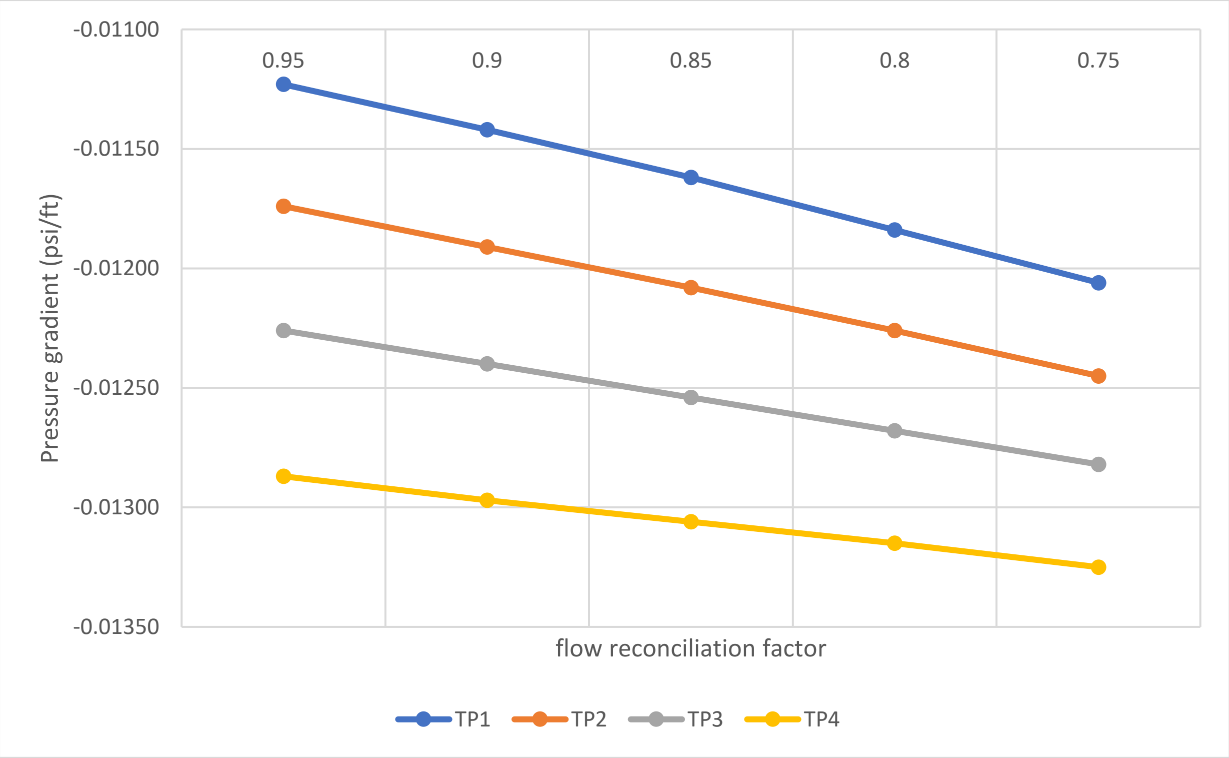


Figure 44. Leak simulation at different positions on 6-inch flowline evacuating 6000bpd.

8.4.3 *Discussions*

The use of pressure gradients has eliminated the main shortcoming of using pressure differential for leak monitoring which is the dependency of the pressure monitoring point to the leak point being investigated. As can be seen from figure 44 if we know the reconciliation factor and the respective pressure gradients at various sections of the pipeline, then we can detect the position of leak. Example, if the RF is 0.9 and the recorded pressure gradient is -0.01150psi/ft then we can say that the leak occurred between TP1 (but nearer to TP1) and TP2. Through interpolation, we could say that the leak is at 0.22L from the same datum where TP1 was assessed as 0.2L. The use of pressure gradient has therefore been demonstrated as a capable technology for use in the estimation of leak point on pipelines especially in single leak situations. The next set of experiments following on this finding would be used to verify the relationship between the pressure gradients for varying pipe diameters with flow rate for a given pipe length.

8.5 Pressure gradient relationship to volume flow rate

The objective of this study was to find a way of estimating leak points without the necessity for simulation or reading graphs or nomograms already generated for the given pipeline. This study is basically a test of an AI workflow of trying to analyse a given pipeline with the data generated from itself through the monitoring of pressure gradient relationship to volume flow rate in each pipeline section. The different dimensions used for the evacuation of different parameters for this analysis is as shown in figure 45 below.

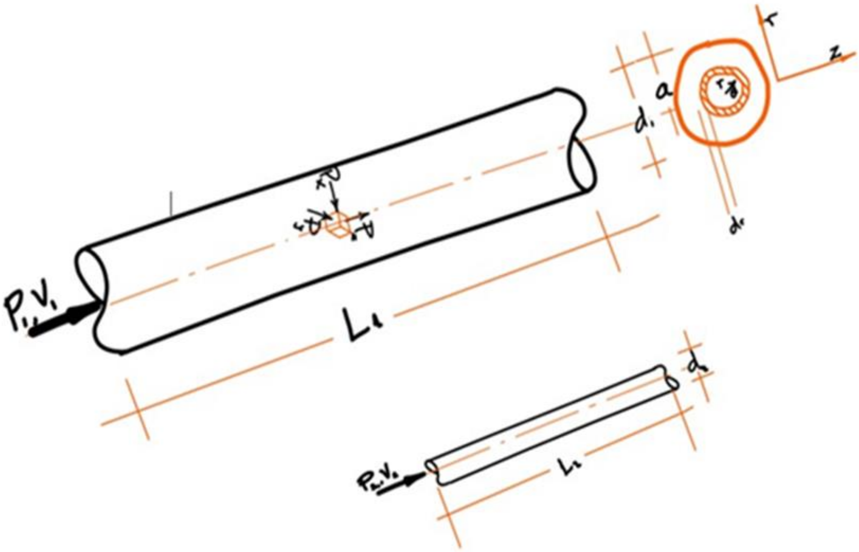


Figure 45. Volume flow rate and pressure gradient relationship

In figure 45 :

V = Volume flow rate in bpd

L is pipe length.

d is pipe dimeter.

r is pipe radius.

$\vec{V} = (u_r, u_\theta, u_z)$ is flow velocity in the r, $\boldsymbol{\theta}$ and z direction.

μ is the viscosity of the evacuated fluid.

P is pressure.

The complete description and derivation of the Navier Stokes equation for an incompressible, isothermal, Newtonian (constant density and constant viscosity) fluid flow with

Velocity $\vec{V} = (u_r, u_\theta, u_z)$ in cylindrical coordinates could be found on most fluid mechanics books and particularly as documented (KTH Royal Institute of Technology Stockhom, 2020) could be written as

Continuity equation

$$\frac{1}{r}\frac{\partial(ru_r)}{\partial r}+\frac{1}{r}\frac{\partial(u_\theta)}{\partial\theta}+\frac{\partial u_z}{\partial z}=0$$

r component

$$\rho\left(\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial\theta}+\frac{{u_\theta}^2}{r}+u_z\frac{\partial u_r}{\partial z}\right)$$
$$=\frac{-\partial P}{\partial r}+\rho g_r+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right)-\frac{u_r}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial\theta^2}-\frac{2}{r^2}\frac{\partial u_\theta}{\partial\theta}+\frac{\partial^2 u_r}{\partial z^2}\right]$$

θ component

$$\rho\left(\frac{\partial u_\theta}{\partial t}+u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial\theta}+\frac{u_r u_\theta}{r}+u_z\frac{\partial u_\theta}{\partial z}\right)$$
$$=\frac{-1}{r}\frac{\partial P}{\partial\theta}+\rho g_\theta+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_\theta}{\partial r}\right)-\frac{u_\theta}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial\theta^2}+\frac{2}{r^2}\frac{\partial u_r}{\partial\theta}+\frac{\partial^2 u_\theta}{\partial z^2}\right]$$

Z component

$$\rho\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial\theta}+u_z\frac{\partial u_z}{\partial z}\right)=\frac{-\partial P}{\partial z}+\rho g_z+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial\theta^2}+\frac{\partial^2 u_z}{\partial z^2}\right]$$

A particular solution of the Navier Stokes equation in cylindrical coordinates as depicted in figure 45 has been solved (Ugaz, 2020) as reproduced in Appendix I to present the relationship between the flow rate and rate of change of pressure gradient in any flow evacuation system as

$$V=\frac{\pi r^4}{8\mu}\frac{\Delta P}{L}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad \text{Equation 8.1}$$

Some experiments were designed to verify this result and thereafter used to design another set of experiments for leak verification. The pressure gradient variation with flowrate for the 6-inch pipe is shown in figure 46 while the pressure gradient variation with pipeline diameters evacuating 2000bpd and 6000bpd are shown as figure 47 and 48, respectively.

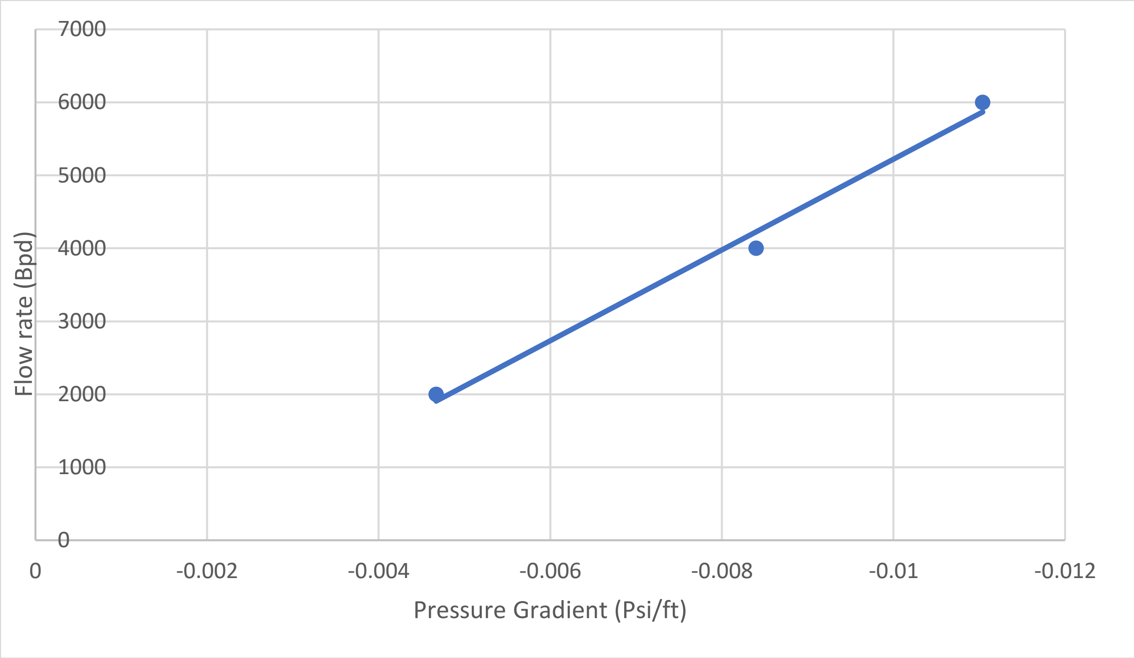


Figure 46. Variation of flowrate V with pressure gradient

The flow rate – pressure gradient relationship in figure 46 is a straight line whose slope could be used to determine the effective viscosity of the fluid that generated the pump characteristics using the relationship:

$$Slope = \frac{\pi r^4}{8\mu}$$

The slope in Figure 46 was used to estimate the live crude viscosity as 0.3cp for the crude from the two wells simulated in PIPESIM. This process of using the output from PIPESIM to re calculate a property of the crude (viscosity) whose evacuation was simulated in PIPESIM is a software calibration process. Since the re calculated viscosity is exactly the live crude viscosity from the evacuated two wells we can confirm the validity of PIPESIM model created for this delivery pipeline.

Equation 8.1 could also be written as `

$$V - v_l = \frac{\pi r^4}{8\mu}\frac{\Delta P}{L} \quad \text{Equation 8.2}$$

where the LHS and RHS of equation 8.1 do not balance initially, the leak or stolen volume rate v_l could be added on the LHS to represent leak such that the two sides of the equation could balance. This concept was verified as a way of leak quantification as part of the new process in this research.

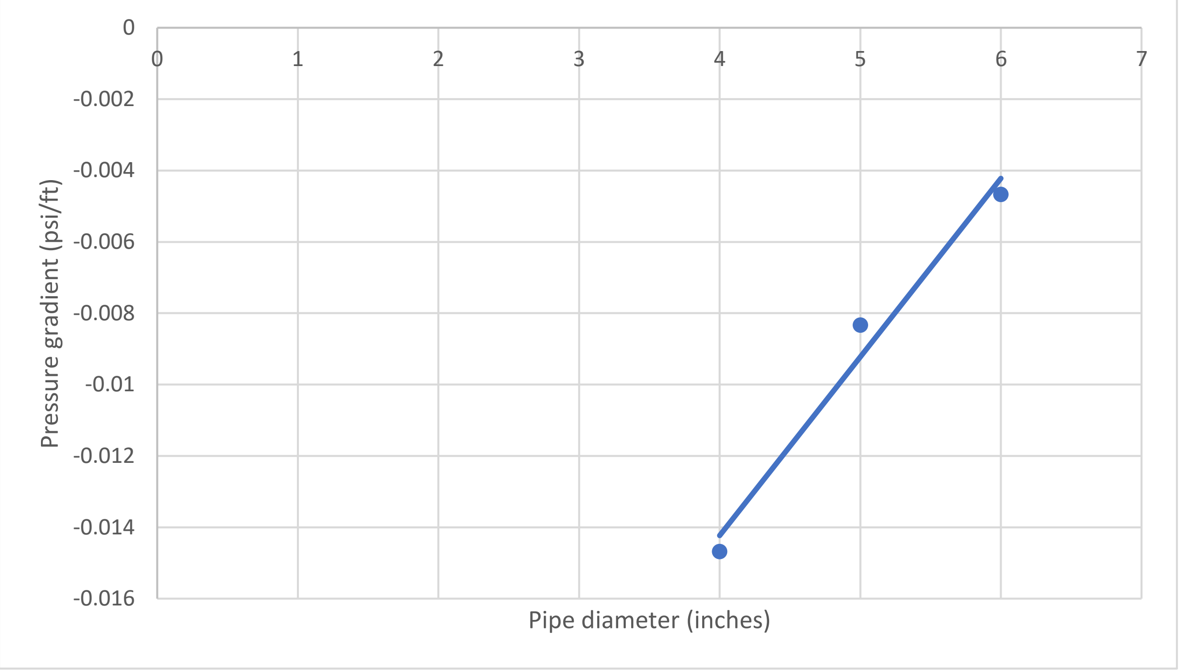


Figure 47. Pressure gradient variation with diameter at 2000bpd without leak

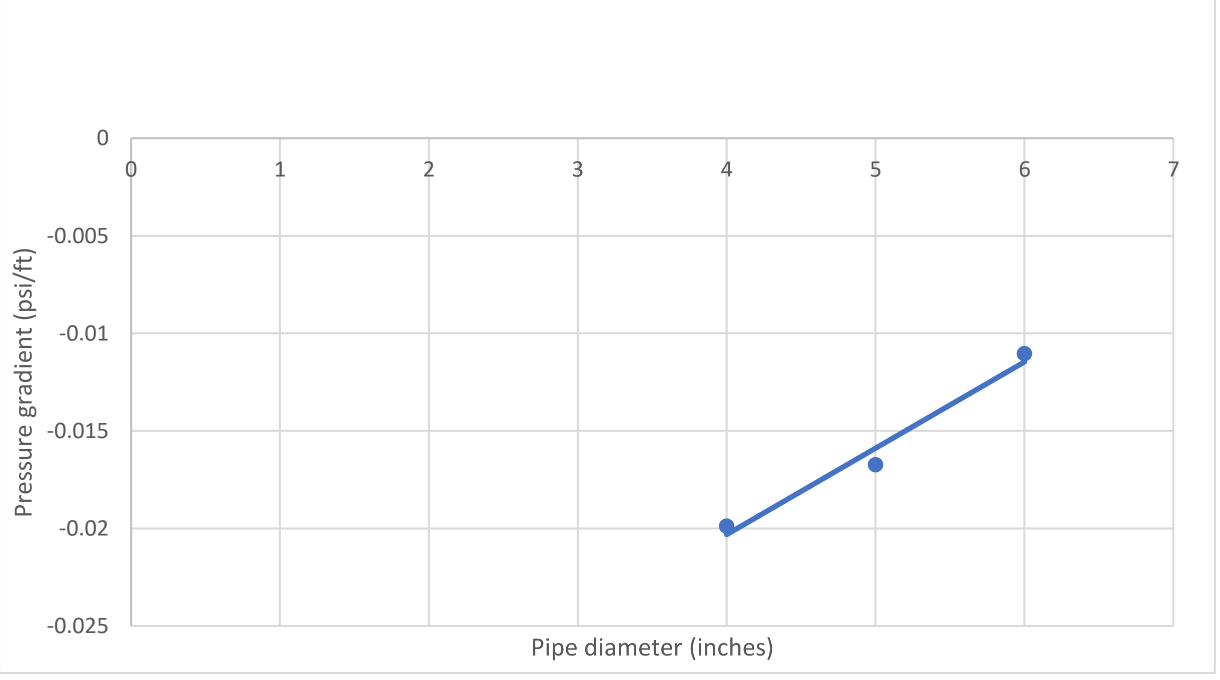


Figure 48. Pressure gradient variation with diameter at 6000 bpd without leak

Figure 46, 47 and 48 could be said to represent a robustness check of the PIPESIM software models created.

8.6 Chapter summary

The theoretical basis for the use of pressure gradient for leak detection has been presented based on analogous comparison to subsurface reservoir engineering practices. One of such practice is using fluid gradients to determine fluid contact planes. Another practice is using reservoir pressure depletion to determine cumulative volume produced from well-defined reservoirs. The relationship between pressure gradient and volume flow rate in pipes for steady state incompressible fluid using Navier Stokes equation was also studied. Input variables to a simulated experiment was accurately back calculated using output results of the PIPESIM simulation experiment. This agreement was taken as a validation of the robustness of PIPESIM simulation software as well as a calibration of the PIPESIM flow simulation models created as part of this study.

Having demonstrated that pressure gradients could be used to determine the precise point of leak in a single leak situation, there is need now to evaluate the possibility of multiple leak detection.

9 MULTIPLE LEAK INVESTIGATION & NEW PROCESS IMPLEMENTATION

9.1 Introduction

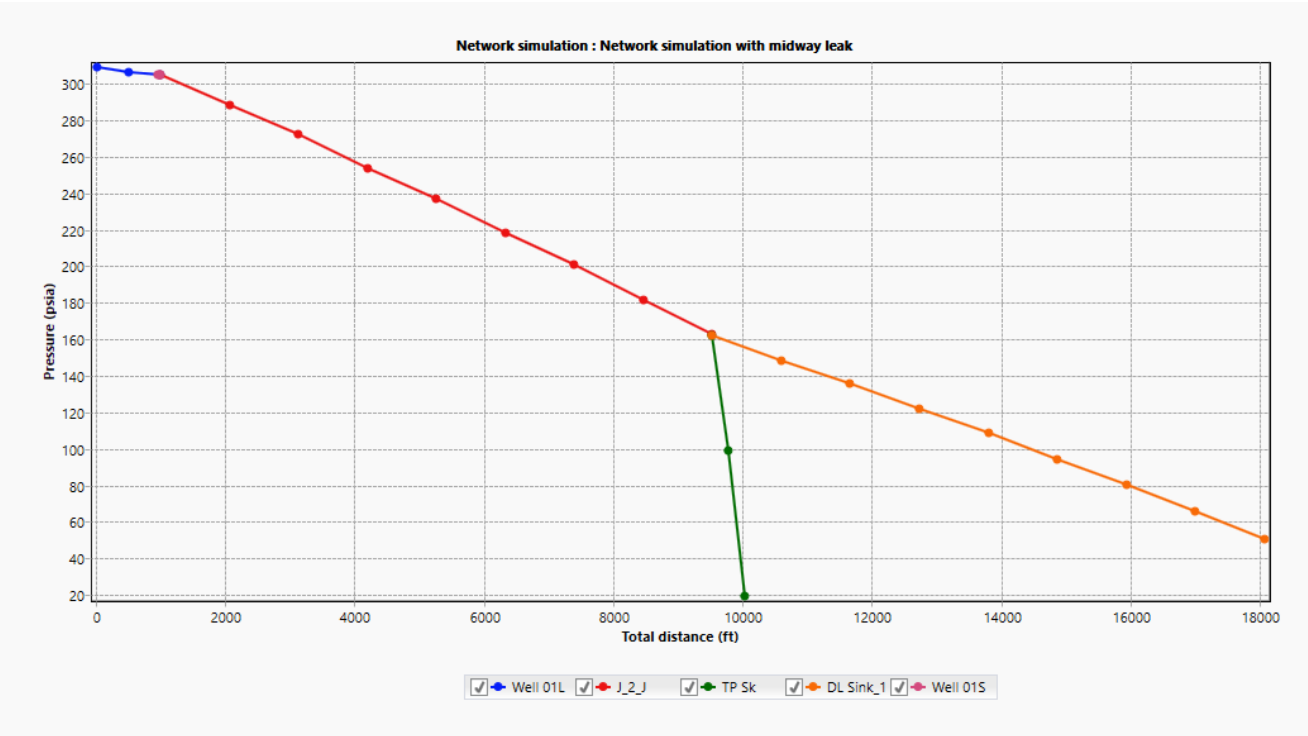
We have demonstrated that pressure differentials, as well as pressure gradients could be used to precisely determine point of leak during fluid evacuation process. This approach still requires some manual computation and sometimes the development of nomograms to augment this finding with the quantification of leak rate at predicted leak points, hence this focussed further study on the use of analytical methods or any other improved methods for complete leak detection and leak rate estimation.

It can be argued as highlighted in Pressure gradient method for leak detection, that if the rate of reservoir pressure decline can be used to estimate cumulative production in a well-defined hydrocarbon reservoir, we could investigate the use of rate of trunkline pressure decline from steady state during crude evacuation for the estimation of leak rate or stolen crude. The solution to Navier stokes equation presented the relationship of volume flow rate as directly proportional to pressure gradient as documented in Pressure gradient relationship to volume flow rate. This therefore means that if the volume flow rate is reduced due to leak, then the pressure gradient is also expected to reduce so some studies were conducted to verify this assertion for the quantification of leak rate at predicted leak points. Also, since pressure gradient is a vector, some additional experimental studies were undertaken for the assessment of leak rate estimation using vector manipulations. This smart vector analysis is in support of the chosen post leak data diagnostic smart operations technology. As documented in Smart fields operations synopsis page 101 the technology solution for the crude oil theft monitoring in the Niger delta was delivered based on vector analysis of real-time, online pressure measurements based on post-leak data diagnostic smart operation.

Having demonstrated that the knowledge sought in this dissertation is achievable, some minimum requirement for the practical implementation of this new process, detailing the strategy for pipeline digital information acquisition system and how such data is to be used for the proposed new smart process for pipeline integrity monitoring, is introduced.

9.2 Gradient intersection method for leak point detection

The results of the pressure profile due to midway leak from the experimental setup in page 160, is represented below:



From the above pressure plot we could derive two equations for the two straight lines passing through points (1000, 305), (9530, 162), (18060, 51) and find the point of intersection which would represent the point of leak.

The straight line between (1000, 305) and (9530, 162) which passes through any set of points (x_1, y_1) could be represented as

$$y_1 = -0.0167x_1 + 321.76$$

Similarly, the straight line between (9530, 162) and (18060, 51) that passes through any point (x_2, y_2) could be represented as

$$y_2 = -0.0130x_2 + 285.89$$

The x and y in the above equations represent trunkline distance and pressures respectively from a given locus which could be from the far upstream trunkline evacuation point. By solving the intersection of these two lines we will get the point (9694, 160) as the point of intersection of both lines, and this would represent the point of leak as simulated. Similarly, if we have more than one leak, we could use the same analytical method to determine the points of leak. The only requirement here is that we must plot all the pressure points first, then generate the equation for each line, before solving the equations for points of intersection which would represent leak points.

This use of intersecting straight lines is similar to the process for GOC and OWC estimation in reservoir engineering as shown in figure 49.

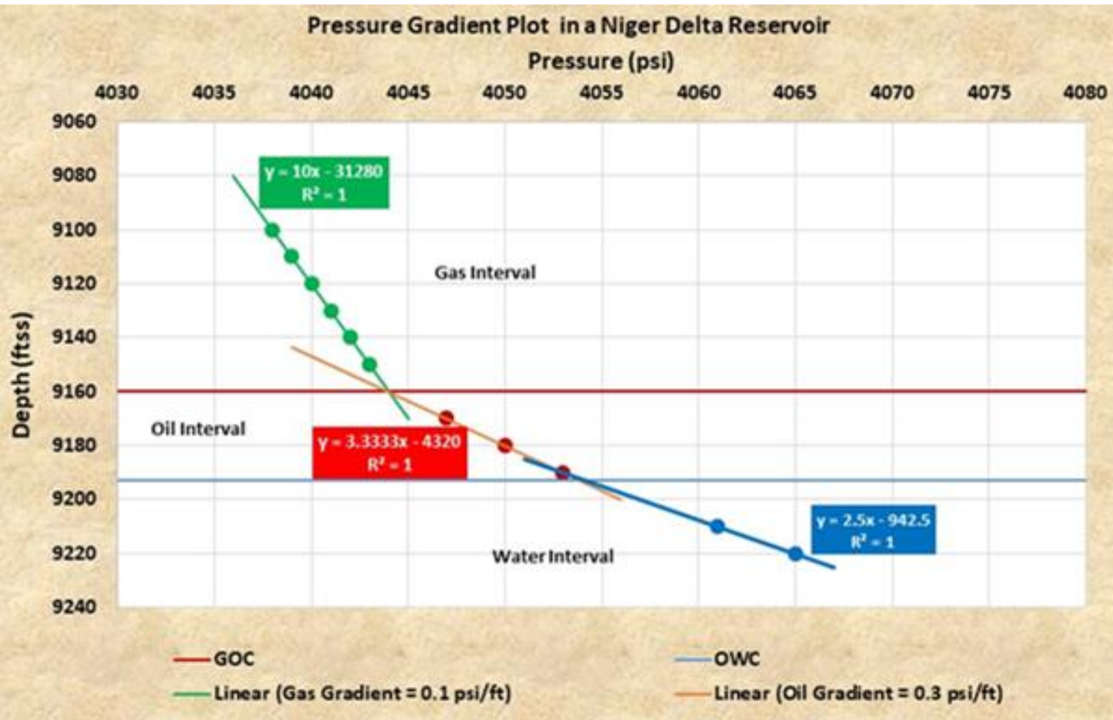


Figure 49. Estimation of GOC and OWC using fluid pressure gradient plots.

Figure 49 shows the estimated equations for the three pressure gradient lines used in reservoir engineering fluid contact estimation process. Graphically or by solving a pair of the intersecting equations gives the point of intersection and by so doing we could get two points which will represent the GOC and OWC and their respective pressures at the respective contact planes. A similar method could be applied in pipeline crude multiple leak investigation through pressure monitoring at several points.

Feng and Zhang (2004) also demonstrated the use of double sensor pressure gradient method together for leak point detection. Their leak point locating experiment involved using four pressure sensors (two on each side of simulated leak) to locate simulated leak point on their experimental pipeline.

9.3 Pressure gradient vector analysis

This study is to investigate the use of pressure gradient changes during crude evacuation for the estimation of rate of leak or stolen crude. A conservative vector field is a vector field that is the gradient of some function whose line integral is path independent (Marsden & Tromba, 2003). This makes pressure gradient a vector, suggesting utility for leak prediction and monitoring. The other properties of the vector are that it should have magnitude and direction, additive, and remains a vector after multiplication (or division) with a scalar.

If

$AC = AB + BC$ ……………………………………………………….………Equation 9.1

We can consider equation 9.1 as a vector equation to represent the result of pipeline gradient changes during crude transportation. In this case as demonstrated earlier:

AC represents the pressure gradient after a leak.

AB represents the pressure gradient before a leak.

BC represents the pressure gradient effect due to leak.

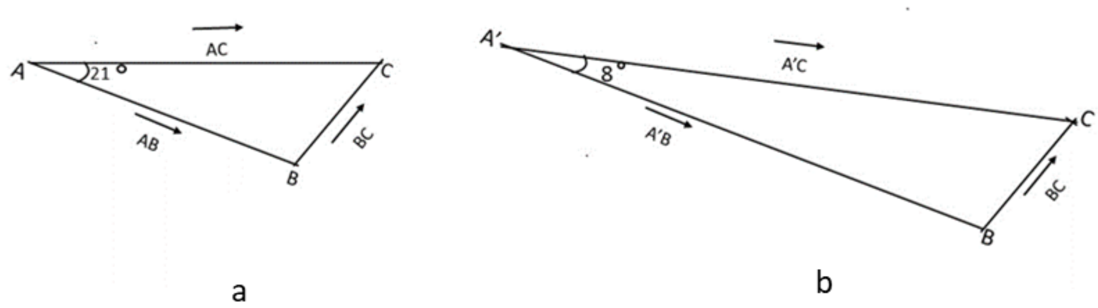


Figure 50. (a) Leaking system vector addition. (b) Scalar vector multiplication at constant leak situation

Figure 50a is a graphical representation of equation 9.1 and shows that without a leak AB would be equal to AC and the difference between AB and AC continually increases with increasing leak rate. This means that with continuous increasing leak rate, the enclosed angle between AB and AC increases. This concept was investigated for leak rate prediction. Figure 50b shows how resultant vector magnitude and direction is influenced when a component vector is manipulated with a scaler. It should be noted that the vector component BC is maintained constant in figure 50b. If we multiply AB with a scaler, say 1.8 a new vector A'B will result, having a different size but same direction. The resultant vector A'C as a result of addition of this new vector A'B to a known vector BC will result to A'C which will have different magnitude and direction as shown in figure 50b. Through the multiplication of one vector component with a scalar in figure 50b, the enclosed angle in the resultant vector from this manipulation has changed from 21° to 8° such that

A'C=A'B+BC ………………………………………………………………. Equation 9.2

It should be noted that the vector AB was enlarged by multiplication with a positive number greater than 1.0. This enlargement could be assumed to represent additional inflow during fluid evacuation. If so, one can assume that we can decrease the vector AB by multiplying with a number <1.0 to emulate inflow reduction. This also raises the question of what happens when AB is multiplied with a negative number. Initial investigations suggest this could represent a reversal of the energy system for the fluid evacuation.

Some experimental pressure gradient vector studies were therefore undertaken to see if through any form of pressure gradient vector analysis during crude evacuation one could monitor pipeline integrity using pressure measurements only. The study tests an AI workflow of trying to analyze a given pipeline with the data generated from itself during crude evacuation using the Post leak data diagnostic method AI workflow described in section 5.4. This analytical method could be used to determine an infinite number of leaks but is unable to quantify the respective leak rates at each leak point without additional data processing. Equation 8.1 and other methods involving vectors were further studied on how they could be used to determine the leak rate at each respective leak point.

9.4 Pressure gradient relaxation method for leak rate estimation

9.4.1 *Setup and data generation methodology*

A fluid evacuation pipeline without a leak could be represented more mechanistically as a uniformly loaded elastic beam that is fixed at one end but free to slide at the other end as shown in figure 51A. A leak at any point will introduce an additional piezometric force, supposedly in opposite direction as depicted in Figure 51B.

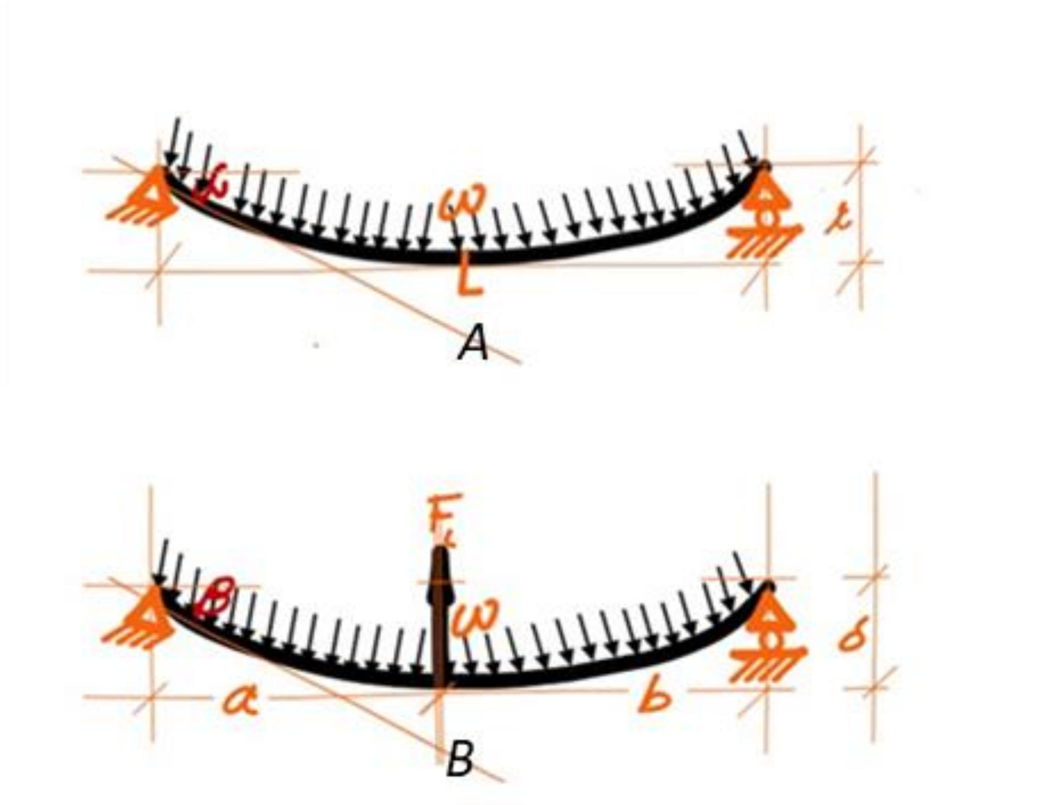


Figure 51. (A) Non leaking fluid evacuation structural analogue (B) Midpoint leak fluid evacuation structural analogue

If ω represents a uniformly distributed weight in a structural member, then the same ω is analogous to the average pump pressure used in a pipeline fluid evacuation system. Also, if F_L is considered a point load in an elastic structural loading, we could say that the same F_L in the structural member is analogous to piezometric force due to fluid leak in a pipeline fluid evacuation system. If α represent the pressure gradient without a leak, or the deflection due to uniform load, respectively for the two systems and β represents the pressure gradient in a leaking system for a pipeline evacuation system or the deflection due to both the point load and uniformly distributed load in the structural system. Let δ and ε represents the max deflections due to fluid evacuation without a leak and with a point leak for the hydraulic system or their respective equivalents in the structural systems as depicted in figure 51A and 51B, respectively. The relationship between the forces on both systems on one hand and δ and ε on the other hand were not evaluated here but could be an area of further research.

It has been demonstrated that pressure gradients calculated from a pipeline evacuation pressure profile could be used to determine the point of leak. Also, experiments have shown that the pressure decline, from established trend, due to leak is directly proportional to the rate of leak. This angular displacement method based on figure 51 was investigated in a leak simulation experiment as depicted in figure 52.

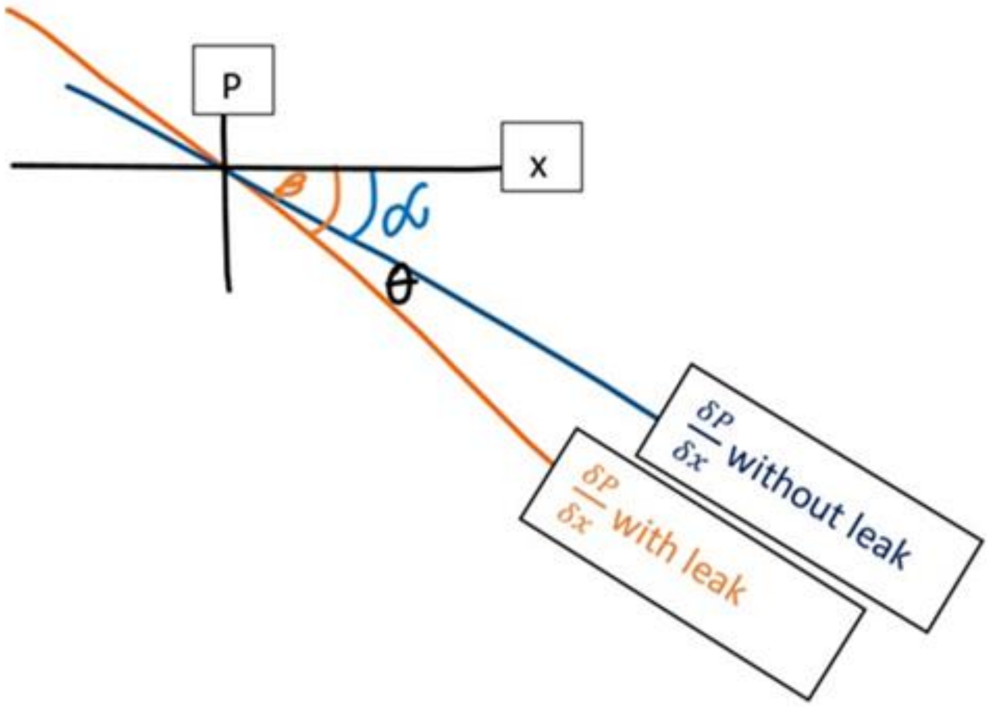


Figure 52. Pipeline fluid vector diagram during fluid evacuation

Using pressure gradient as a vector, then we could use results of table 5, which had earlier been used for verification of Pressure gradient response to volume, to estimate the pressure depression (or relaxation) angle due to a leaking system as a vector as illustrated in figure 52.

If α represent the slope without a leak, and β represent the slope in a leaking system.

Then the depression angle θ due to leak can be estimated as β - α and used to determine the leak rate and the point of leak using the trigonometrical equation

$$\text{Tan}(\theta) = \tan(\beta - \alpha) = \frac{\tan(\beta) - \tan(\alpha)}{1 + \tan(\beta)\tan(\alpha)}$$

The same data used in figure 44 was reprocessed using the angular depression method and table 6 shows RF, leak rate and pressure gradients from a model evacuating 6000 bpd crude through a 6inch pipeline system. The calculated depression angles (θ) due to leaks are as shown in table 6.

Table 6. Calculated depression angles (θ) due to simulated leaks

Zone	RF	Leak rate	Slope due to leak	tanβ-tanα	1+tanβtanα	tanθ	θ
TP1	1.00	0	-0.011044	0.000000		0.000000	0.000000
TP1	0.95	400	-0.011229	-0.000185	1.000002	-0.000185	-0.010623
TP1	0.90	800	-0.011423	-0.000379	1.000004	-0.000379	-0.021712
TP1	0.85	1200	-0.011625	-0.000581	1.000006	-0.000581	-0.033288
TP1	0.80	1600	-0.011836	-0.000792	1.000009	-0.000792	-0.045351
TP1	0.75	2000	-0.012055	-0.001011	1.000011	-0.001011	-0.057927
TP2	1.00	0	-0.011044	0.000000		0.000000	0.000000
TP2	0.95	400	-0.011740	-0.000696	1.000008	-0.000696	-0.039867
TP2	0.90	800	-0.011909	-0.000865	1.000010	-0.000865	-0.049546
TP2	0.85	1200	-0.012083	-0.001039	1.000011	-0.001039	-0.059542
TP2	0.80	1600	-0.012263	-0.001219	1.000013	-0.001219	-0.069852
TP2	0.75	2000	-0.012449	-0.001405	1.000016	-0.001405	-0.080495
TP3	1.00	0	-0.011044	0.000000		0.000000	0.000000
TP3	0.95	400	-0.012262	-0.001218	1.000013	-0.001218	-0.069775
TP3	0.90	800	-0.012398	-0.001354	1.000015	-0.001354	-0.077560
TP3	0.85	1200	-0.012537	-0.001493	1.000016	-0.001493	-0.085516
TP3	0.80	1600	-0.012678	-0.001634	1.000018	-0.001634	-0.093624
TP3	0.75	2000	-0.012823	-0.001778	1.000020	-0.001778	-0.101898
TP4	1.00	0	-0.011044	0.000000		0.000000	0.000000
TP4	0.95	400	-0.012873	-0.001829	1.000020	-0.001829	-0.103132
TP4	0.90	800	-0.012965	-0.001921	1.000021	-0.001921	-0.108862
TP4	0.85	1200	-0.013058	-0.002014	1.000022	-0.002014	-0.114591
TP4	0.80	1600	-0.013152	-0.002108	1.000023	-0.002108	-0.120321
TP4	0.75	2000	-0.013247	-0.002203	1.000024	-0.002203	-0.126051

These results are plotted in figure 53 below:

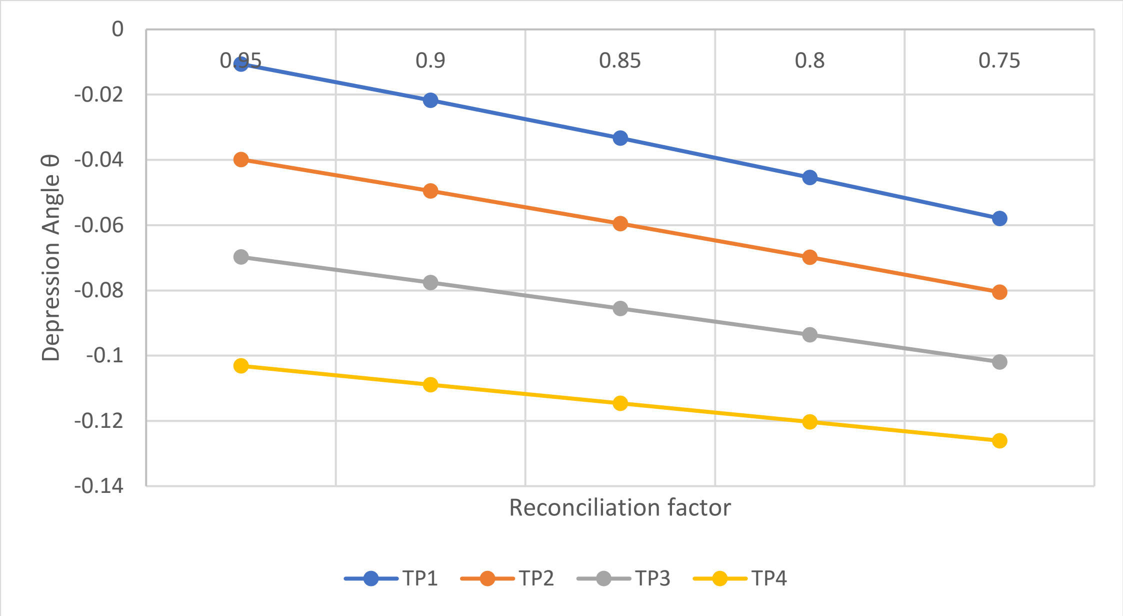


Figure 53. Depression or relaxation angle θ due to leak

9.4.2 *Discussion*

Figure 44 and Figure 53 were generated using the same leak simulation results. Figure 44 was based on pressure gradient analysis while figure 53 was based on the depression or relaxation angle enclosed by the pressure gradient, so in effect the depression angle analysis is an improvement upon the pressure gradient analysis method. The results from using the enclosed angle plot is a set of equally spaced lines representing leaks from equally spaced points at equal fractional pipeline lengths. This is in line with the particular solution of the Navier Stokes equation generated earlier (Ugaz, 2020). There is little overlap of the pipeline characteristic leak lines generated based on depression angle due to leak as shown in figure 53 and these curves are usable nomogram for pipeline leak detection. The pressure depression plot from figure 53, like figure 44, is a straight line which further demonstrates that the angle of depression is proportional to the rate of leak. It is known from trigonometry that the absolute value of the tangent of a number is equal to the absolute value of the tangent of the negative number, hence the negative sign on the depression angle calculated in table 5 is based on the sign convention adopted in figure 52. In reality, and as can be seen from the table of results, a leaking system represents a pressure relaxation or depressurization on the pipe walls hence the gradient vector is in the opposite direction and hence of positive signage. This analytical method is therefore renamed pressure gradient relaxation (instead of depression) method as any leak in a pipeline will lead to depressurization or relaxation.

Figure 53 can be used as a nomogram that is based on dimensionless parameters of RF, fractional lengths, and enclosed angle and could be used to determine the leak rate as well as point of leak anywhere on the modelled 6-inch pipeline. Once there is pressure variation from expectation, we could use this generated nomogram (figure 53) and the knowledge of operating RF at the terminal to determine the exact point of leak and leak rate. This nomogram has thus demonstrated the revised research question on leak rate and point of leak determination through pressure measurements using the post leak data diagnostic smart operations process.

This new finding could be used as a concluding confirmation, for single leak situation, to this dissertation that: ***If we have a way of continuously measuring the steady state conditions of a pipeline at regular intervals (say 5 or 10km) during operation, then we could, through deviations trending from the steady state operation from monitoring sensors, determine the point of leak or crude oil theft and quantify leak rate or theft.*** The deviation being monitored here could be the pressure gradient relaxation angle due to leak. It should be noted that the accuracy of this post leak data diagnostic method depends on the spacing between the data acquisition points. E.g., if the pressure sensor data are received at 5km interval we could say that the accuracy of the applied post-leak data diagnostic process, especially with respect to leak rate estimation, would be better than those estimated from a situation where the pressure sensor data are received at 10km interval or above.

9.5 Leak rate determination in multi-leak situation

We have demonstrated that the pressure gradient relaxation angle on a pipeline used for crude evacuation is directly proportional to the rate of leak. We have also shown that the point of leak on such a pipeline could be determined by Pressure gradient method for leak detection as documented in page 158. Also, from a particular solution to the Navier Stokes equation during the discussion on Pressure gradient relationship to volume flow rate we have also proven that volume flow rate relationship with the pressure gradient is governed by:

$$V = \frac{\pi r^4}{8\mu}\frac{\Delta P}{L}$$

An attempt at quantification of leak rate during crude oil theft using the above relationship was investigated using two methods proven in this research.

9.5.1 *Leak rate determination in multi-leak situation using PGR method.*

The pressure gradient relaxation (PGR) approach involves using the volume flow rate and pressure gradient relationship to monitor the leak rate in a pipeline fluid evacuation system. The objective of this experiment as sketched in figure 54 was to simulate multiple leaks and evaluate the pressure gradients relaxation angles corresponding to the various sectional leaks such that equation 8.1 could be used to back calculate the respective leak rates that yielded the recorded pressure gradient relaxations (PGRs).

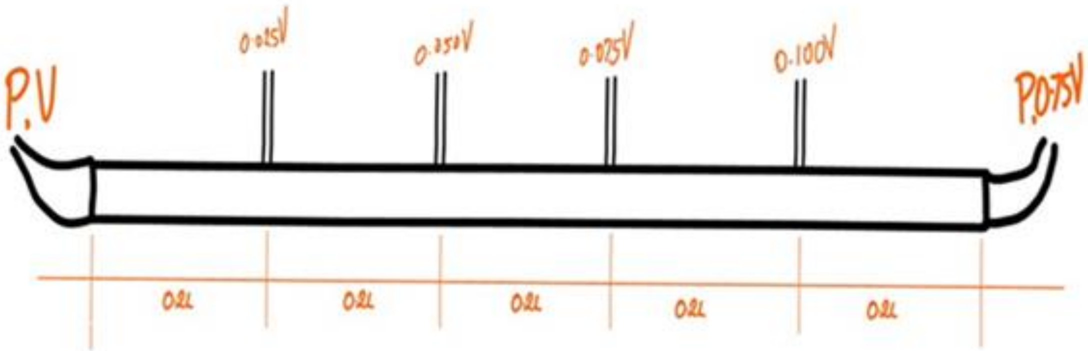


Figure 54. Leak rate estimation experimental set up

The volume flowing through a section of the pipeline after a leak v_{l_i}would be represented by

$V = (V - v_{l_i})$ where v_{l_i} $is\ the\ leaking\ volume\ at\ the\ i^{th}\ secton\ of\ the\ pipeline$ and

$$\frac{\Delta P_{i+1}}{L_{i+1}}\ would\ represent\ the\ presure\ gradient\ at\ the\ i + 1\ section\ of\ the\ pipeline\ after\ the\ v_{l_i}\ leak$$

Therefore, by substituting for V and pressure gradient at the $i + 1$ section of the pipeline in equation 8.1 we could calculate the leak v_{l_i} in the i^{th} section of the pipeline. The process here would involve working from “knowns to the unknowns” by working from source to sink and step wisely estimating respective leaks in multiple leak situation.

Some experiments were therefore simulated in PIPESIM to test this PGR method for multiple leak detection as shown in figure 55.

Figure 55. PIPESIM multiple leak simulation experiment

The first experiment involves two leaks of 1000bpd and 1500 bpd at tapping points 1 and 3 designated as TP1 and TP3, respectively. Figure 56 shows the pressure plots from where we could identify the two leak points as simulated.

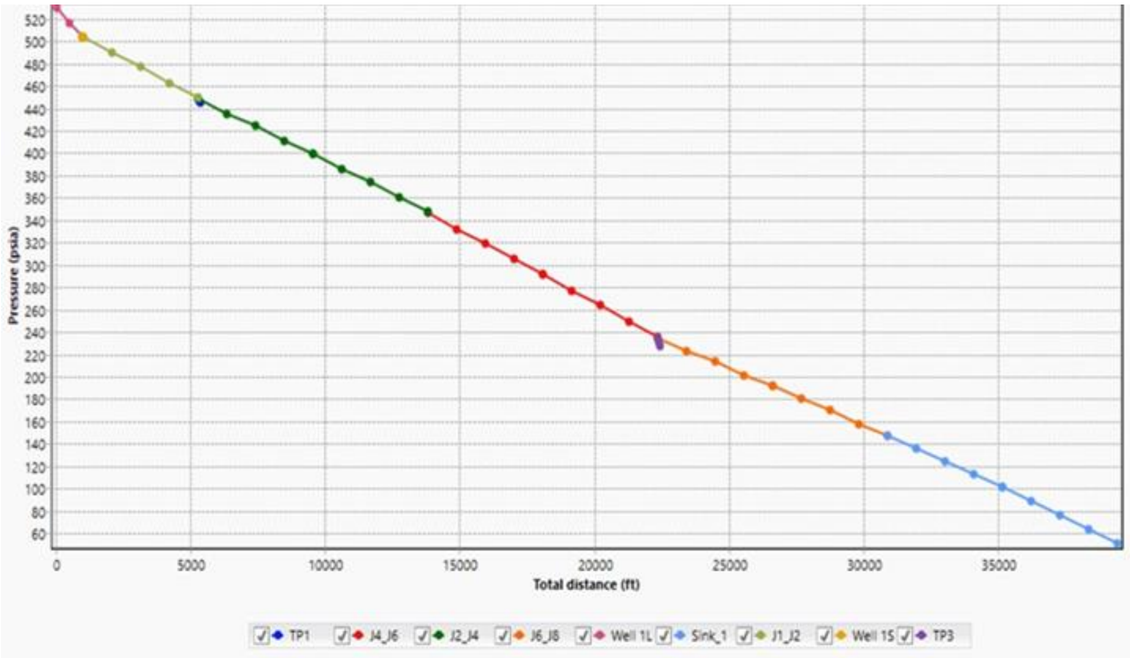


Figure 56. Delivery line transmission pressure profile with two leaks

Having identified that there are two leaks at 5250ft and 22310ft as modelled, the respective leak rates were evaluated using equation 8.1 through the calculation of the pressure gradient slopes on the above plot. To achieve this, we would evaluate the pressure gradients at three points: before TP1 leak; after TP1 leak to demonstrate the effect of TP1 leak and after TP3 leak to demonstrate the effect of both TP1 and TP3 leaks. The principle used here were demonstrated in Pressure gradient relaxation method for leak rate estimation page 178.

Pipeline slope before the first leak at TP1

$$\frac{\partial p}{\partial x}\lim_{J_1\to j_2} = \frac{448.3121 - 503.4499}{5249.612 - 984.2992} = -0.0129270238\, psi/ft$$

Pipeline slope after the first leak at TP1

$$\frac{\partial p}{\partial x}\lim_{J_4\to j_6} = \frac{234.1172 - 348.2906}{2310.87 - 13780.24} = -0.0133849903\, psi/ft$$

Pipeline slope after the second leak at TP3

$$\frac{\partial p}{\partial x}\lim_{J_6\to j_8} = \frac{147.5197 - 219.4181}{30841.49 - 22310.87} = -0.0084282737\, psi/ft$$

The above pressure gradient calculations would lead to three respective equations derived from equation 8.1 below.

$$V = \frac{\pi r^4}{8\mu}\frac{\Delta P}{L}$$

Where $K_i = \frac{\pi r^4}{8\mu}$

$6000bpd = K_0 * (-0.0129270238)\, psi/ft$ ....Equation .9.1

Similarly

$6000 - v_{TP1} = K_1 * (-0.0133849903)$ ... ...Equation 9.2

$6000 - v_{TP1} - v_{TP3} = K_2 * (-0.0084282737)$ … … . .. ………………………...Equation 9.3

$v_{TP1} + v_{TP3} = 2500$……………………………………………………………Equation 9.4

v_{TP1} and v_{TP3} represent the simulated leak rates at tapping points TP1 and TP3 respectively.

To estimate K_o from equation 9.1 both the LHS and the RHS should be on the same unit of gf, cm, s.

Equations 9.1, 9.2, 9.3 and 9.4 has more unknowns than available equations so could not be solved without some assumptions. Any assumption unfortunately would lead to some errors, but we can still make some assumptions and test whether the errors emanating therefrom are acceptable.

If we assume that

$K_0 = K_1 = K_2$ … Equation 9.5

then using this value of K and solving equation 9.1 in corresponding units yields

$$K_0 = \frac{6000(bbl/d) * 158987.295(\mathrm{cm}^3/bbl)}{(24 * 60 * 60 s/d)} \frac{30.48 cm/ft}{-0.0129270238\ (psi/ft) * 70.303(gf/\mathrm{cm}^2)}$$

K_0= -370,290.427 cm^2/gfs

Using the assumption $K_0 = K_1 = K_2$ and solving equation 9.2 would yield.

$$v_{TP1} = 1{,}043\ bbl/day$$

Similarly using equation 9.3 and the value of the first leak rate v_{TP1}

$$v_{TP3} = 1{,}835\ bbl/day$$

The estimated total leak rate from the use of the PGR method above is 2878bpd but the total simulated leak was 2500bpd. If we use this knowledge which is what was received at the terminal during the leak simulation, then some adjustment must be made using equation 9.4 so that our revised leak rate at simulated tap point 3

$$v_{TP3r} = 1{,}457\ bbl/day$$

Similar evaluations were made for a second experiment which involved 1000bpd and 2000bpd leaks at TP1 and TP3, respectively. The results of both experiments are summarised as shown in table 7 below with the respective error margins. Equation 9.4 is not part of the proposed PGR process but an additional information arising from the knowledge of RF which was especially useful. Without the use of this information the errors in estimating the second leak rate would be unacceptable. This unacceptable error is due to the assumptions made on the value of K which ideally varies with varying remaining flow after each new leak. Table 7 summarises the results of this PGR evaluation.

Table 7. Leak rate prediction results using solution of PGR method.

	Evacuated Volume in bpd	Leak point	Simulated leak rate (bpd)	leak rate from PGR process alone (bpd)	Error due to PGR alone (%)	leak rate from PGR Process and RF (bbl/d)	Error due to PGR and RF (%)
1	6000	TP1 TP3	1000 1500	1043 1835	4.3 22.3	1043 1457	4.3 -2.8
2	6000	TP1 TP3	1000 2000	973 1702	-2.7 -14.9	973 2027	-2.7 1.4

The first leak rate estimation using this PGR method is quite accurate but unfortunately the second leak rate prediction error is unacceptably high. However, the RF information was used to control the estimate of the second leak in a two-leak situation. This luxury of using the RF to control the prediction result after the first leak therefore means that this PGR process could not be used beyond two leak situations as this would lead to unacceptable errors beyond the second leak. This error beyond the second leak estimation is due to the assumption made in equation 9.5 about K in all pipe section irrespective of remaining flow after leak in those sections. Transmission flow constant K is a system characteristic which is related to volume flow so equation 9.5 is invalid and this makes the use of this method for multi-leak estimation beyond the second leak erroneous. As stated in the Solution pathfinder mind map (page 112) the assumption that K is constant throughout the length of the pipe, irrespective of the leaks at respective section was a convenient (but progressively wrong assumption with increasing leak) assumption needed in a blind guess for some semblance of the truth in simple leak experiments. We now know that K is not constant so the usability of this PGR process for multi leak prediction beyond the second leak will depend on further study for evaluation of the dependency of K, for respective sections, on the flow volumes through such pipeline sections. Otherwise, this PGR process would be valid in the evaluation of a two-leak situation only.

9.5.2 *Leak rate determination in multi-leak situation using EAVR method.*

A second attempt at quantifying the leak rate at each leak point in multi leak situation involved the use of enclosed angle vector relaxation (EAVR) method which is based on Pressure gradient relaxation method for leak rate estimation discussed in page 178. Some additional four (4) experiments were conducted to test the option of using the EAVR methods for the estimation of two or more leak situations. These leak experiments were based on 6000bpd delivery line fluid evacuation through a 6in pipe some 12km in length. The four leak simulation results were compared with the result of the no-leak situation. The comparison of transmission pressures with no leak situation were first used to generate pressure gradients as shown in table 8. This comparison is described as pipeline leak characteristic data. The pipeline characteristic curve is the pressure response of any pipeline without a leak and some documentation of anticipated deviation for some given leak position and corresponding leak rate. The pressure gradients from this pipeline data were then used to estimate the enclosed angle vector relaxation EAVR as shown in table 8. This EAVR method is for quantification of leak whose locations has been identified through other means. The shaded areas in the table 8 represent the areas where the leaks have been simulated and confirmed from PIPESIM pressure gradient plots.

Table 8. Pressure gradient in psi/ft calculated during leak simulation.

Experiment	No leak	0.8TP1_1.6TP2	0.5TP2_1.5TP3	1.0TP2_1.0TP3	1.2TP2_1.2TP3
Slope before TP1	-0.01116718	-0.01228414	-0.01205337	-0.01215404	-0.01236821
Slope after TP1	-0.01209651	-0.01340670	-0.01313498	-0.01325283	-0.01350557
Slope after TP2	-0.01339797	-0.01015110	-0.01349876	-0.01238196	-0.01214624
Slope after TP3	-0.01508198	-0.01063918	-0.01105711	-0.01105711	-0.01015110
Slope after TP4	-0.01742151	-0.01120598	-0.01231157	-0.01231157	-0.01120598

The EAVR uses the Pressure gradient relaxation method for leak rate estimation page 178 and the result of the analysis is presented in table 9. The angles α and β in this experiment represent the pipeline pressure gradient without leak and pipeline pressure gradient with leak respectively. The enclosed angle θ represents the pipeline EAVR due to leak and can be expressed as

$$\mathrm{Tan}(\theta) = \tan(\alpha - \beta) = \frac{\tan(\alpha) - \tan(\beta)}{1 + \tan(\alpha)\tan(\beta)}$$

Table 9. Estimation of pipeline EAVR due to leak.

Simulation	$tan(\alpha)$	$tan(\beta)$	$tan(\alpha) - tan(\beta)$	1- $tan(\alpha) - tan(\beta)$	Tan(θ)	θ
0.8TP1_1.6TP2	-0.01209651	-0.0134067	0.001310197	1.000162174	0.001309984	0.007506
0.8TP1_1.6TP2	-0.01339797	-0.0101511	-0.003246868	1.000136004	-0.00324643	0.186006
0.5TP2_1.5TP3	-0.01339797	-0.01349876	0.00010079	1.000180856	0.000100772	0.005774
0.5TP2_1.5TP3	-0.01508198	-0.01105711	-0.004024866	1.000166763	-0.00402419	0.230568
1.0TP2_1.0TP3	-0.01339797	-0.01238196	-0.001016011	1.000165893	-0.00101584	0.058203
1.0TP2_1.0TP3	-0.01508198	-0.01105711	-0.004024866	1.000166763	-0.00402419	0.230561
1.2TP2_1.2TP3	-0.01339797	-0.01214624	-0.001251726	1.000162735	-0.00125152	0.071707
1.2TP2_1.2TP3	-0.01508198	-0.0101511	-0.004930873	1.000153099	-0.00493012	0.282473

As already discussed, the EAVR due to leak is proportional to the leak rate. This means that EAVR can be plotted for any given pipeline and used to back calculate what leak that may have created the EAVR at any point. The simulated leak rate is plotted against EAVR (θ) and as expected it is a straight line as shown in figure 57. This line is called the evacuation pipeline system descriptive model (SDM) and could be used to determine leak anywhere on this given pipeline as propounded by this dissertation. This SDM can be used to estimate the leak rate at any point on this pipeline once a leak point is identified and we are able to calculate the EAVR at that leak point. Seven out of the eight experiments are in very close agreements with the predictions of pipeline SDM.

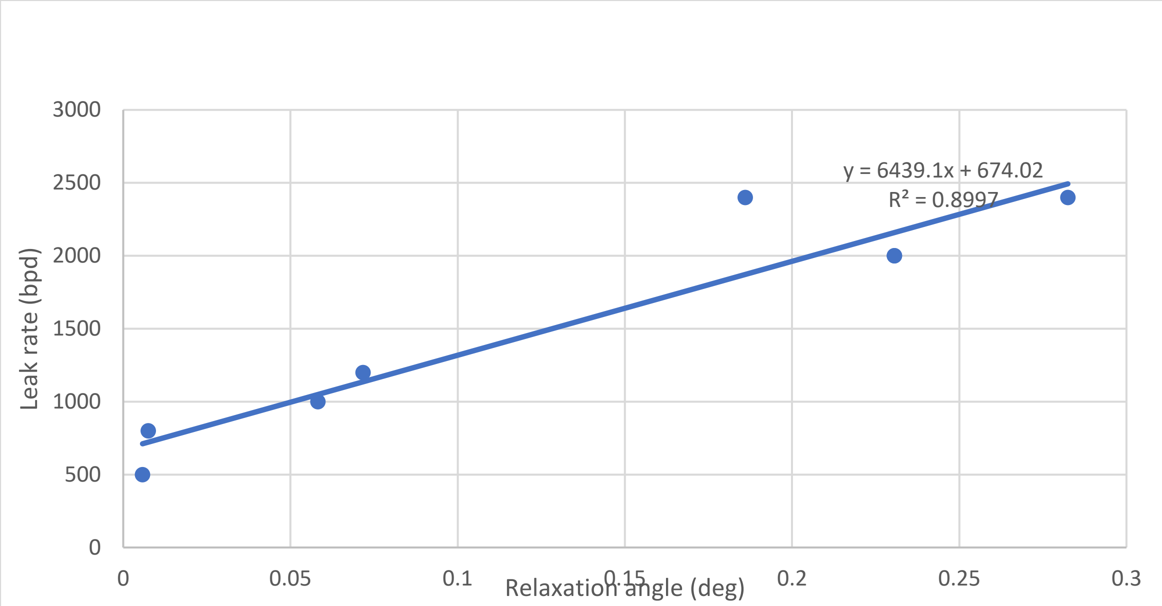


Figure 57. Delivery line system curve for leak detection based on leak relaxation angle.

As shown in figure 57, R^2 of 0.8997 means that the leak rate prediction accuracy based on the newly developed EAVR concept is 89.97% of the actual leak rate prediction and this is very good. R^2 for *Microsoft excel*, or a statistical mean squared error as it is generally known is a measure of event prediction quality of an estimator. The maximum error from using this new process to simulate two leak situations during eight leak experiments is about 10% as can be seen in figure 57, hence the use of the EAVR method was adopted for the recommended smart process for pipeline integrity monitoring using the pre-leak data diagnostic AI workflow.

A forecast can be made from the generated SDM for quantification of leak rates once the leak position is known as shown in figure 58.

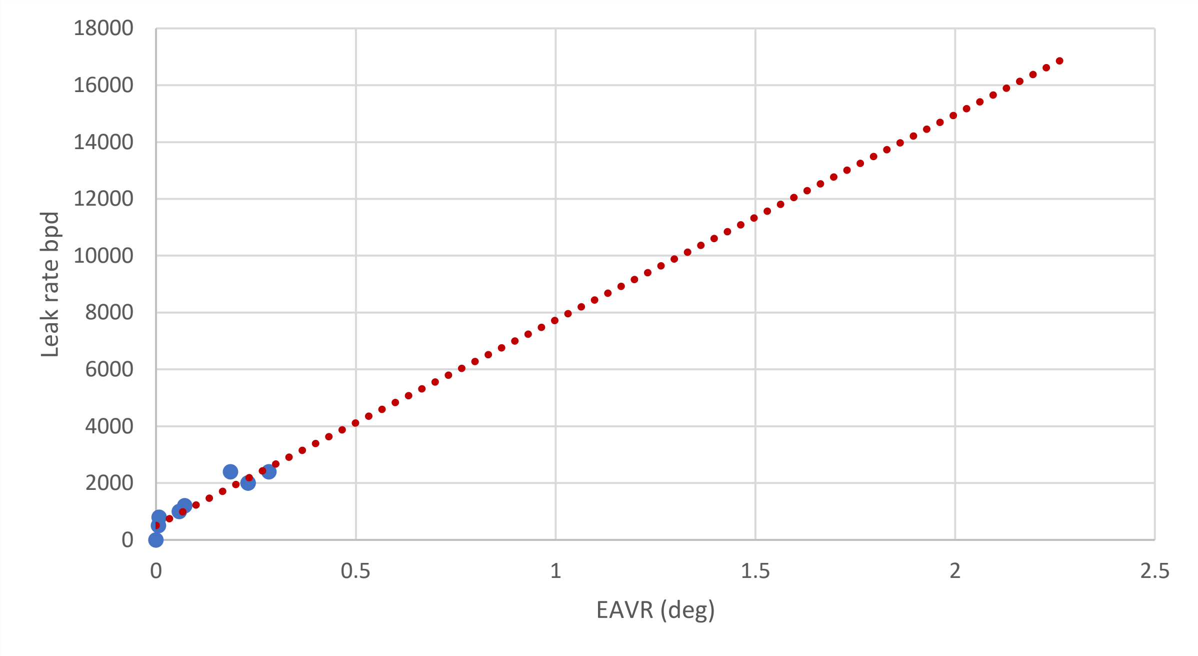


Figure 58. SDM for modelled 6inch trunkline

9.6 Implementation of proposed post-leak data diagnostic leak detection method.

Having achieved an acceptable prediction accuracy in leak point and leak rate estimation based on post leak data diagnostic smart operations process it is now a good point to discuss the practical implementation of the proposed smart process for pipeline integrity monitoring.

The concept of plan-do-check cyclic process introduced in section 1.1, Introduction, page 14 is aimed at continuous improvement. This plan-do-check continuous improvement operations can be considered analogous to a conical spring where the planer axis represents the projected *plan-do-check* loop while the vertical axis represents the continuous improvement after each cycle as conceptually represented in the conical helix in figure 59. Using this example, it should be noted that the planner diameter of the conical spring continuously reduces as it pitches upwards. This represents a convergence in solution that follows any completed *plan-do-check* loop.

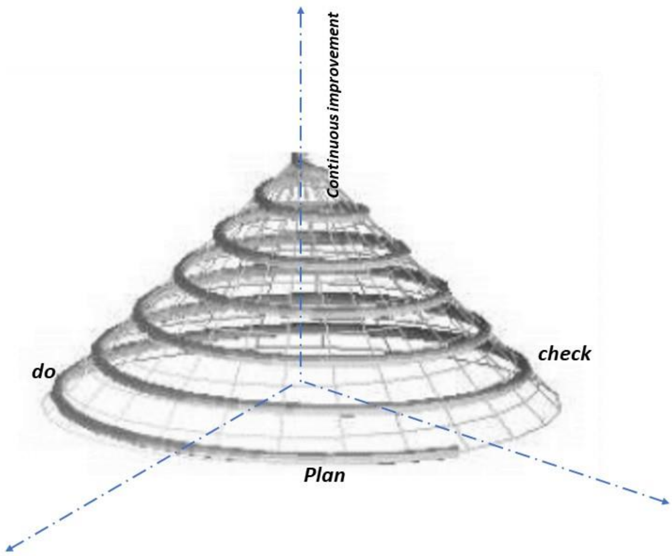


Figure 59. Conceptualisation of plan-do-check continuous loop as a conical spring.

It was discussed that one of the reasons why some level of smartness has not been applied to pipelines could be because it is considered a consumable in the oilfield development equation but that seems to be changing. Digital twins which offer detailed representation of real-world products will be the innovation backbone of the future, enabling a conceived system to be simulated and tested before a physical prototype is built (Gaus, 2019). So how do we contribute to this desired change in pipeline transportation process?

9.6.1 *Uncertainty management and reduction of leak signal variability*

Uncertainty represents a state of limited knowledge where it is impossible to exactly describe the existing state, a future outcome, or more than one possible outcome. Uncertainty arises in partially observable and/or stochastic environments, as well as due to ignorance, indolence, or both (Norvig & Thrun, n.d.). According to Norvig[9] and Thrun[10] in their definitions relating to uncertainty management.

- An environment is called fully observable if what your agent can sense at any point in time is completely *sufficient* to make the optimal decision i.e., its sensors can see the entire state of the environment. That is in contrast to some other environments where agents need *memory* to make the best decision.
- Deterministic environment is one where your agent's actions uniquely determine the outcome. In stochastic environment, there is certain amount of randomness.
- A discrete environment is one where you have finitely many action choices, and finitely many things you can sense. For example, in chess there is finitely many board positions, and finitely many things you can do.
- In benign environments, the environment might be random. It might be stochastic, but it has no objective on its own that would contradict your own objective. For example, weather is benign. Contrast this with adversarial environments, such as many games, like chess, where your opponent is really out there to get you.

Some discussions on how the spacing for each pressure monitoring point (5km or 10km) will affect the accuracy of leak detection has been documented in section 9.6.4 on Smart process for pipeline integrity monitoring, page 203. We can say that the errors associated with leak estimation using the new process recommended by this research depends, among other things, on the frequency of pressure sampling points. There are also some errors that could arise due to input measurement and sampling techniques that are not able to capture pressure differentials due to leaks. The input parameters are limited to only pump pressures and volumes at respective spiking points and the pipeline pressures at pressure monitoring points on the pipelines.

As documented in section 3.4.6.2 on Vibration modelling page 90, one of the reasons why the use of external vibration sensors for this research was not progressed is that the level of vibration generated during crude evacuation in large pipes are small and could be masked by background noise. Having chosen to progress the post leak data diagnostic method using

[9] Peter Norvig (born December 14, 1956) is an American computer scientist. He is a director of research at Google, LLC, and used to be its director of search quality.
[10] Sebastian Thrun (born May 14, 1967) is CEO of Kitty Hawk Corporation, and chairman and co-founder of Udacity. Before that, he was a Google VP and Fellow, a Professor of Computer Science at Stanford University. At Google, he founded Google X and Google's self-driving car team. He is also an Adjunct Professor at Stanford University and at Georgia Tech.

pressure gauges, how do we ensure that measurement variability and background noise does not mask the pressure changes due to leak which the transducers and the new process are supposed to detect? Figure 60 shows a recorded pressure variability of over 100psi during a high-rate gas well test. A typical pipeline operates at about 500 psi far upstream and at about 100psi at terminal discharge. If the employed pressure transducers have up to 50psi variability at any point, then it means that we are unable without some data processing to detect leaks that are caused by pressures around 50 psi leak.

The use of *averages* as a method to reduce leak signal variability, which is based on the principle that as sample size grows its mean will get closer to the average of the whole population, can be applied to reduce variability in the leak signal and in input data for this recommended new process (Henrie, Morgan; Carpenter, Philip; Nicholas, 2016). We can use the gas-well clean-up in figure 60 to demonstrate data smoothening for reduction of measurement variability.

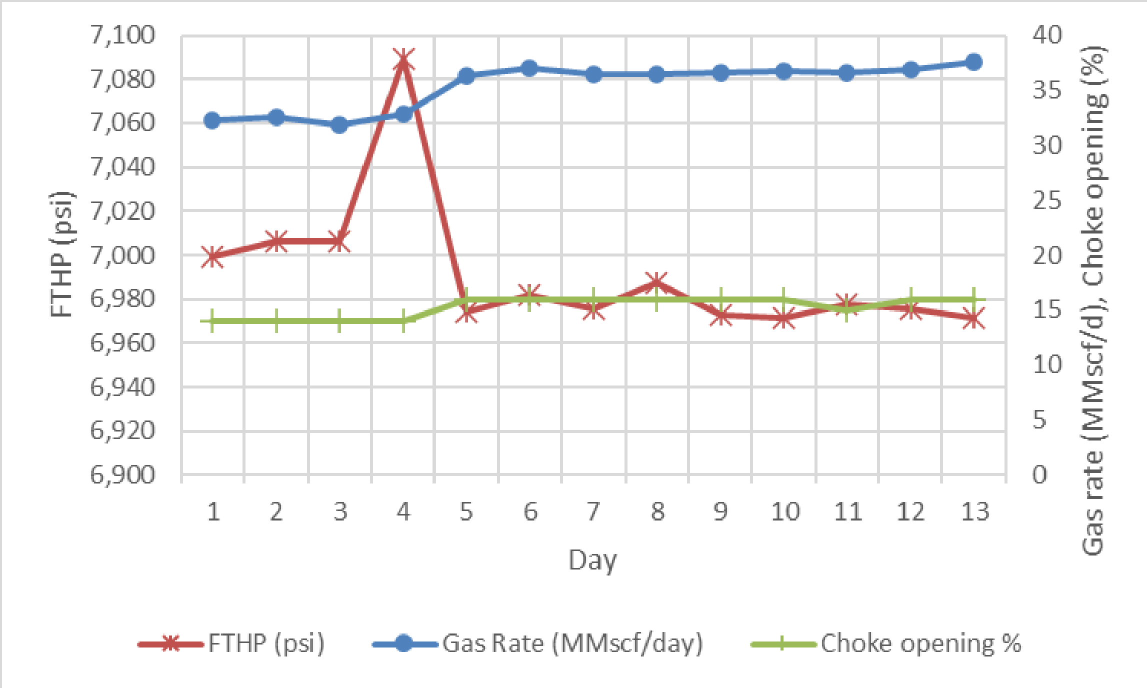


Figure 60. Gas-well clean-up test data

We can isolate the FTHP from figure 60 and see how the FTHP variability can be reduced. In this approach, we could use a simple three-day moving average, or we can use a time-weighted three-day average (0.5, 0.3 & 0.2) to reduce the FTHP data variability as shown in figure 61 below.

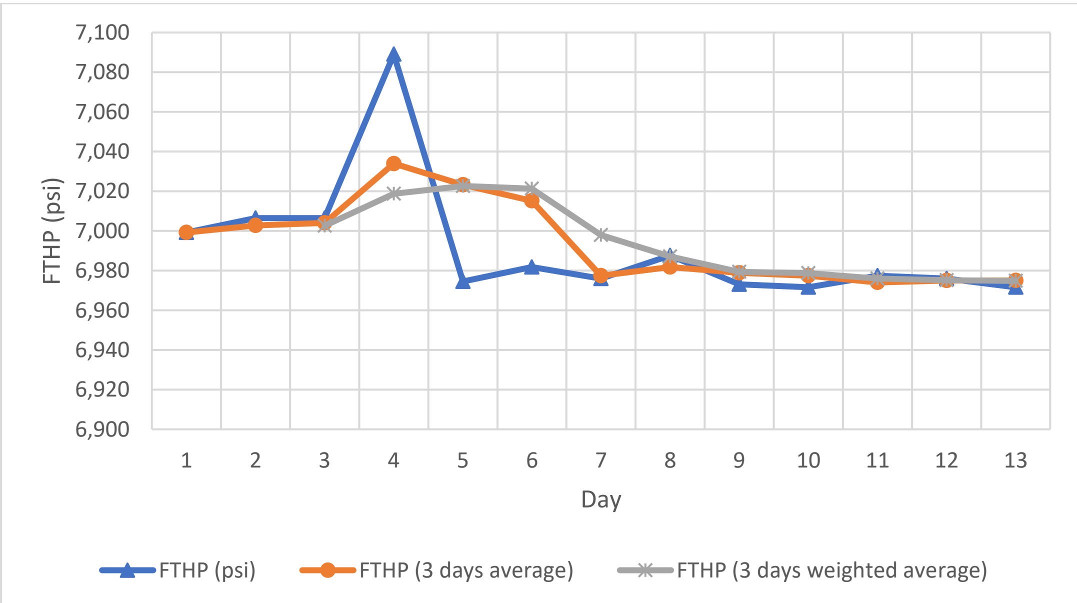


Figure 61. FTHP data averaging methods

Using the time weighted average, we can reduce the maximum measured pressure variability in this example from 100 psi to 10 psi. The weighted average curve is also a much smoother curve and shows the transition between a transient clean up mode and a steady state gas flow operation. We can see from this gas well data that any additional inflow (or leak) due to pressure of about 20psi could be masked by signal noise during the transient region (before the 7th day) using the raw data and the weighted average data but with a properly smoothened curve from the 10th day the same inflow or leak leading to 20psi or below would be detectable.

Pipeline transmission data could be continuous as in most digital gauges and could be averaged over the day, over and hour or over quarter of an hour. We have shown through experimentation in section 7.7 that 5% crude loss over a 100,000-bpd trunkline would lead to a 5psi pressure differential in a particular Niger delta trunkline. This therefore means that the continuous pressure data from such fluid evacuation must be smoothened with enough data to detect 5psi pressure drop if we plan to use the new process recommended in this research to detect such a leak through pressure monitoring.

In summary, depending on what pressure differential being targeted, we must smoothen the transmitted pressure curves to a level where such level of target pressure can be detected.

9.6.2 *Digital Twining in pipeline fluid evacuation process*

The concept of digital twinning was first introduced in Smart fields operations synopsis page 101. The digital twin (DT) was also described as a process that could be used for health usage and monitoring system (HUMS) for pipeline fluid evacuation process using the selected research concept of post-leak data diagnostic process. It involves detailed modelling of the transmission pipeline, inclusion of pressure monitoring sensors as part of the pipeline, design of data acquisition architecture for capture and transmission of required data from the pipeline to processing centre for analysis. The analysis involves processing the pump volume and pressure measurements and the pipeline transmission pressure through the pipeline SDM for the prediction of leak points and corresponding leak rates. A potential architectural diagram for smart pipeline data acquisition system can be conceived as shown in figure 62 below.

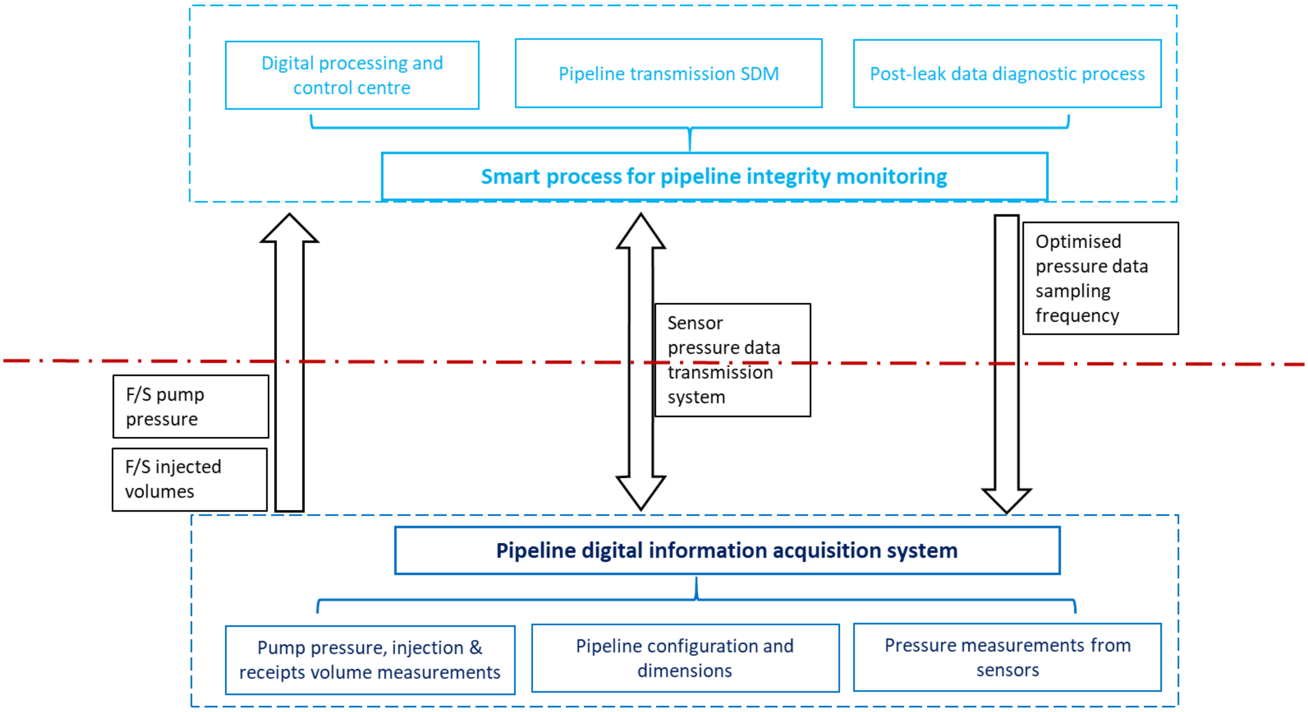


Figure 62. Smart pipeline data acquisition system architecture.

Smart pipelines are now seeing a new generation of sensors that are seamlessly integrated into the pipeline itself. New pipelines will come alive with big data flowing as quickly as the fuel pumped through it. This next generation Micro-Electro-Mechanical Systems, or MEMS may be the future, but existing pipelines can be retrofit with sensors too (Martin, 2018). This retrofit ability is in line with this research proposal that whatever product that arises from this research is retrofittable on existing flowline not minding that these concepts are still futuristic and needed for different needs in different jurisdictions. E.g., the need for this solution is as a result of desperation in Nigeria but the reason for such application in the USA/Canada could be due to regulatory requirements. According to Martin (2018) oil pipelines typically transport liquid at pressures between 600 and 1000 psi, while natural gas pipelines go up to 1500 psi. “These high pressures are why ruptures can be so serious, and why monitoring and detecting flaws in advance is so important, particularly given the age of some of these pipes. According to the US DOT, more than half are at least 50 years old.”.

The pipeline data acquisition system architecture, as recommended in this research is a coupling, using data transmission and control systems, between the required foundation data for fluid evacuation monitoring and the recommended smart process for pipeline integrity monitoring which is driven by the specific pipeline system descriptive model. The data transmission and control, depending on the level of smart operations sophistication, could involve information transmission, feed forward and feedback loops between the actual pipeline and the virtual pipeline that is represented by the model.

9.6.3 *Pipeline digital information data acquisition system*

Irrespective of the project driver (regulatory or desperation) for the required infrastructure for pipeline integrity monitoring, there is a general agreement that future pipelines will be smart with some form of data acquisition system.

The original basic requirement for pressure measurements at well heads and manifolds is the requirement for installing a Kerotest valve receptor for data acquisition when needed. The Kerotest valve is a spring-loaded one-way needle valve, just like the spring-loaded valve of any automotive tyre, and pressures are recorded by installing a Kerotest valve that can depress the spring so that the system pressure can be recorded as part of surveillance operation. In modern facilities especially where some level of smartness becomes mandatory due to remote locations, the use of these type of valves were replaced with pressure transducers which are wired directly to operations control centre or to an TCP/IP to LAN from where they are transmitted to the operations centre via some SCADA system.

The next generation Micro-Electro-Mechanical Systems, or MEMS may be the future as conceptually depicted in figure 63, but existing pipelines can be retrofit with sensors too, both external and internal to the pipe.

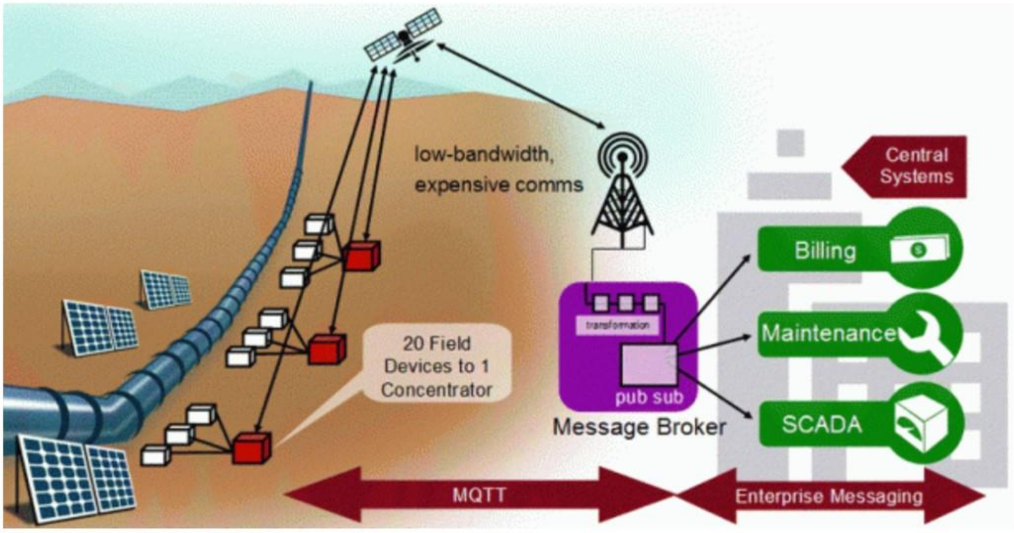


Figure 63. Future MEMS pipeline data acquisition concept (Martin M.J, 2018)

As discussed, the most important data for this concept is the monitored transmission pressures which can be measured with an appropriately sized transducers and transmitted through any suitable *internet of things* (IoT) system to the data digital processing centre for use in leak prediction. The IoT is the interconnection via the internet of computing devices embedded in everyday objects, enabling them to send and receive data[11]. The simplest IoT example being our smart phones which are widely used and wired to their paired devices like watches such that some important critical activities like level of activity (or inactivity), hours of sleep, quality of sleep, body temperature, humidity, stress, and heart rate can continuously be monitored using the watch and recorded on our respective phones. Some remote cameras are also paired with our smart phones such that we can detect visitors to our facilities and even remotely talk

[11] Oxford Languages and Google: https://languages.oup.com/google-dictionary-en/

to such visitors. So why can't this level of monitoring be installed on trunklines and used to monitor crude theft? It should be noted however that the concept presented above can only be operated in a secure area where there are no security challenges so the protection of such IoT facilities is fundamental to the achievement of the suggested new smart process. If vandals can unearth buried pipelines for hot tapping and crude theft it will be very easy to vandalise the installed solar panels and some of the IoT equipment even when there is no visible second-hand value market for the stolen items. One easy way of addressing this is to build manned infrastructure around each nodal IoT installation. Such manned infrastructure could be in the form of the construction of security huts around such IoT infrastructure or building such infrastructure around suitable landmarks like major structures like road or railway crossings etc. The other data needed for the implementation of this new process are the injected volumes and pressures at the respective flowstations such that these data can be transmitted to the operations centre where they can be used to predict leak or anomaly using the new smart process for pipeline integrity monitoring.

9.6.4 *Smart process for pipeline integrity monitoring*

Although, originally conceived as a purely technical solution which is now supported by post-leak data diagnostic method, the technology recommended need some surveillance support to forestall the theft of the infrastructure supporting the recommended technology solution. Cluster IoT centres some 10 or 15 km away from each other, depending on operating cost incremental, are therefore recommended along the pipeline ROW such that continuous data acquisition from these IoT clusters are recorded, transmitted, and used for leak point (and leak rate) determination.

The basis for this new process is the particular pipelines system descriptive model SDM which will be used to continuously generate conformance data using all the data receipt from IoT. The basis for this conformance data is pressure gradient and EAVR and where there is an EAVR, the EAVR will be used to predict the point of leak and estimate the leak rate. It should be noted that where the IoT is powered with renewable energy as shown in figure 63 and depending on the ownership or cost of data transmission we can have a full real-time data acquisition and analysis all the time. But do we really need a twenty-four-hour day online, real time IoT data transmission and usage even when there has been no leak in the past few days. This is where the desirability for optimized pressure data sampling frequency combined feedback and feed forward loop between the pipeline and the IoT is needed such that the pressure sampling frequency could be reduced to once or twice a day as necessary. Such pressure measurements could be instantaneous, or hourly average or daily average data transmission through the IoT. The detailed steps for the implementation of the smart process for pipeline integrity monitoring is discussed in chapter 11 of this dissertation.

9.7 Chapter summary

Having achieved a prediction accuracy of 89.97% in leak rate estimation based on four pairs of data in a simulated leak experiment, we can conclude that we have verified two complementary approaches for estimating leak point and leak rate during fluid evacuation through pipelines. A 100% accuracy in leak point determination had earlier been demonstrated in Gradient intersection method for leak point detection (page 174). The first approach in this new process is the detection of leak points through pressure gradient relaxation method while the second approach is the estimation of leak rates for the respective leak points using enclosed angle vector relaxation.

These analytical methods built on the use of pressure measurements which were derived from experiments in support of post-leak data diagnostic smart fields operations. A detailed technology screening of literature review results had supported the use of smart fields operation for the testing of documented research hypothesis which is based on use of pressure measurements for leak monitoring using the post-leak data diagnostic AI method.

One option for the deployment of this new process would be to develop a fully automated system that reads the required pressures from available monitoring points, processing such data for the generation of the required leak points and thereafter evaluating the corresponding leak rates. Another alternative would be to develop some smart process that requires some human intervention either during data gathering or during parts of the data processing before use in leak detection or leak rate estimation. In both data strategy the objective is to apply the data to a new smart process for pipeline integrity monitoring which is now supported with data. The concept of digital twinning for HUMS for pipeline fluid evacuation process was recommended as part of this new process. It involves detailed modelling of the transmission pipeline, inclusion of pressure monitoring sensors as part of the pipeline, design of data acquisition architecture for capture and transmission of required data from the pipeline to processing center for analysis. The analysis involves filtering and processing the pump volume and pressure measurements and the pipeline transmission pressures through the pipeline SDM for the prediction of leak points and corresponding leak rates.

Data filtering involves strategies to ensure that measurement variability and background noise does not mask the pressure changes due to leak which the transducers and the new process are supposed to detect. The use of weighted averages as a method for reducing leak signal variability, which is based on the principle that as sample size grows its mean will get closer to the average of the whole population was recommended for data filtering.

The relaxation angle due to leak is proportional to the leak rate so a prerequisite for this new process for pipeline Integrity monitoring would be the construction of pipeline system descriptive model (SDM) prior to leak investigation. This research has therefore recommended the documentation of SDM as a standard procedure during pipeline commissioning.

In summary, the research process for this dissertation is based on deductive reasoning and hinged on using available data to support the research hypothesis as a way of demonstrating a new knowledge that crude oil leaks can be identified through pressure measurements has been demonstrated. The research hypothesis which says that “If we have a way of continuously measuring the steady state conditions of a pipeline at regular intervals (say 5 or 10km) during operation, then we could, through deviations trending from the steady state operation, determine the point of leak or crude oil theft and quantify leak rate or theft” was reduced to ability to monitor leaks through pressure measurements only. Some experiments were conducted, and the results of those experiments not only shows that leaks can be monitored through pressure measurements only but yielded the EAVR concept which additionally can be used to quantify leak rate. Having used available data to support our hypothesis we can say that the new knowledge sought has been demonstrated.

Having demonstrated the documented research objective, as well as recommended some additional recovery barriers for the management of loss of containment in the crude oil evacuation HEMP process, marks the end of this dissertation but some further research for reprocessing of fluid flow processes were undertaken for this new knowledge extension of the recommended EAVR process into inflow analysis. The difference between leak and inflow within any space or domain is sign convention. Leaks represent some fluid outflow from a defined domain while inflow represents some fluid movement into the given domain. As a result of this, it is believed that any technology that can be used to detect leak can also be used to detect inflow: hence some further experiments to test the applicability of the demonstrated EAVR into inflow prediction.

10 ADDITIONAL TESTING OF EAVR METHOD FOR LEAK OR INFLOW RATE ESTIMATION

10.1 Introduction

This research objective of establishing a new process for estimating leak points and leak rate during crude evacuation process has been achieved through a combination of experimental results, some fluid mechanical propositions, and some vector manipulation and arguments for confirmation of some physical principles. Central to the support of this new concept was pressure measurements for estimation of transmission pressure gradients for the determination of leak points. Once the leak points are identified, the same pressure gradients used in the identification of leak points can also be used in the estimation of leak rates by comparing pre-leak pressure gradient vector and post leak gradient vector and the angle between them which has been defined as enclosed angle vector relaxation (EAVR).

In the graphical proof of concept documented at Pressure gradient vector analysis it was felt that this EAVR can be used to estimate fluid inflow in addition to leaks. This also sounds logical since the difference between inflow and leak is that one is opposite of the other in sign convention within the domain space being studied. This corollary was tested through two case studies in subsurface engineering.

10.2 Well inflow and choke performance prediction using EAVR.

As part of well delivery process, subsurface engineers predict well potential based on reservoir properties like reservoir pressure, thickness, porosity, permeability, and hydrocarbon saturation. The underlying reservoir influencing sweep parameters are mainly dominated by reservoir development, reservoir compartmentalization and access to reservoir drive energy. Other issues that determine well potential include oil and water contact, gas and oil contact, degree of sand consolidation (for sandstone reservoirs) and size of completion conduit. Although the well production is governed by its deliverability through the inflow equation, there is no reason why the wells inflow, within the wellbore, could not be determined using the EAVR propounded here as conceptually demonstrated.

Table 10 which shows the results of well performance model at different flowing tubing head pressures (FTHPs) in 2016 in a Niger delta field for well performance prediction will be used to test the capability of propounded EAVR method for predicting well inflow.

Table 10. Niger delta well performance prediction table.

	Model 1	**Model 2**	**Model 3**
Flowrate (bpd)	**800**	**1100**	**1350**
FTHP (psi)	**2480**	**2100**	**1850**
Reservoir Pressure (psi)	**2530**	**2530**	**2530**
Reservoir Dept (ftss)	**8785**	**8785**	**8785**

The inflow SDM for the given well can be estimated using its performance at two different chokes. Once the SDM is established, the inflow performance at the third choke or indeed any future choke can be estimated using the established SDM. The choke sizes are not shown in table 10 but their effects are reflected in the varying FTHPs. The only condition here is that the reservoir must be undersaturated or such prediction should not be on a very low FTHP, or choke, where a lot of gas will come out of solution within the well. This condition is necessary as increasing errors would arise as more gases a liberated from the hydrocarbon as the bubble point pressure are attained during transport process from reservoir to the well head.

To apply the EAVR theory we must note that some baseline data is needed. This baseline, which will now be called inflow characteristic curve is based on the well's vertical lift characteristics within the tubing which will now be used to predict additional inflow as expected using the well's SDM. As a result of this, especially in a well's vertical lift estimate, we can use any performance point to represent a point of no-additional inflow. With this point and just another point on a different choke we can plot the well's SDM and use it to estimate future performance of such wells under varying flowing tubing head pressures (FTHP).

The 2016 model showed three predictions of well performance at different FTHPs. We had earlier stated that some baseline is needed to create an SDM for the well. We can use the results of Model 1 (in red fonts) as baseline. Model 1 and model 2 can then be used for the creation of the well's SDM using the EAVR method and see if we can predict the flowrate for model 3 using its FTHP and created SDM. The pressure gradient vector is calculated in the direction of flow between the reservoir pressure, the FTHP and the distance between the reservoir and the wellhead. The well head is assumed to be at 0 feet subsea (ftss). Using vectors, we can determine the EAVR between model 1 and model 2 pressure vectors and use it to calculate an inflow SDM for the prediction of model 3 performance.

The pressure gradient flow vector in model 1 is -0.0056915196 psi/ft.

The pressure gradient flow vector in model 2 is -0.0489470689 psi/ft.

We could, based on table 10, say that the pressure relaxation between model 1 and model 2 yielded additional 300 bpd inflow so that this information can be used to create the required SDM for the well.

Table 11. Baseline and additional inflow data for Well Inflow SDM estimation.

Experiment	tan(α)	tan(β)	tan(α)-tan(β)	1+tan(α)tan(β)	(tan(α)-tan(β))/(1+tan(α)tan(β))	θ
Baseline	-0.005692	-0.005692	0.000000	1.000000	0.000000	0.000000
Additional 300 bpd inflow	-0.005692	-0.048947	0.043256	1.000279	0.043244	2.476124

Table 11 documents the EAVR component computation and can be used to plot an inflow SDM for the well as shown in figure 64. The well bean up is the controlled or gradual open up of a well after completion (construction) or repairs until the designed well production potential is attained, and the process of open up or bean up increases well production while reducing its

FTHP. It should be noted that, as documented in Pressure gradient vector analysis, that without a leak or inflow the pressure gradient vector remains constant hence there is no pressure gradient relaxation or EAVR.

As can be seen from the well's inflow SDM shown in figure 64, the production rate at any given FTHP is governed by

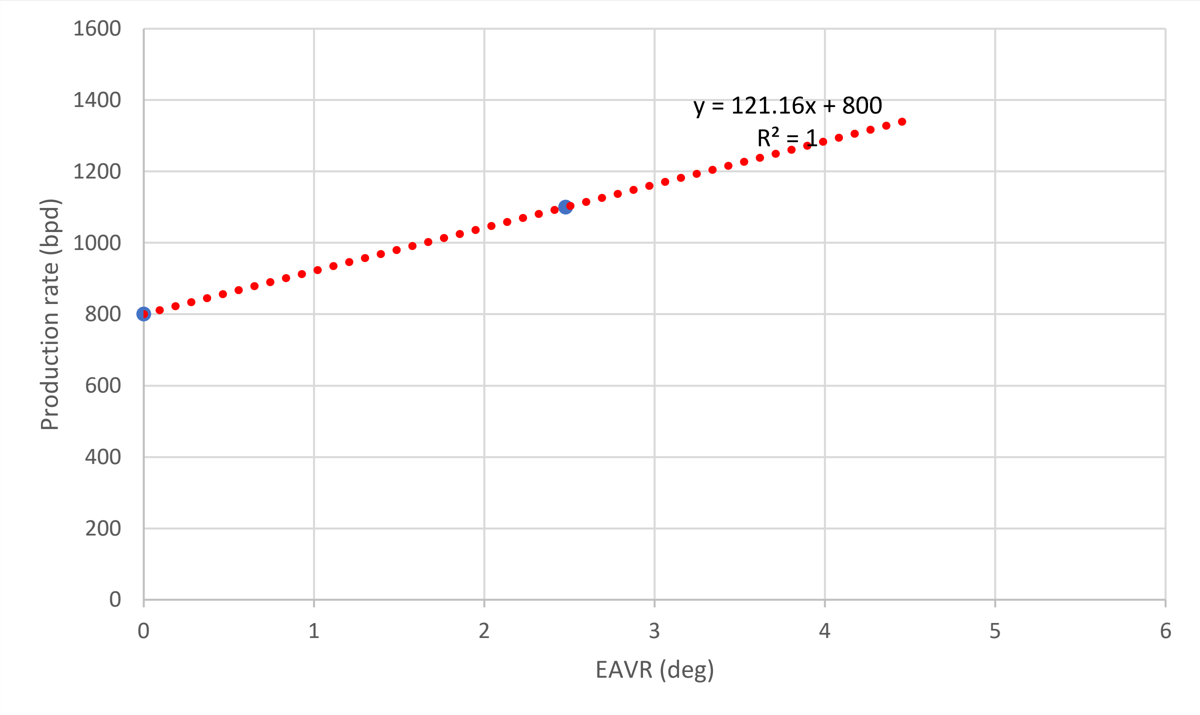


Figure 64. EAVR based on FTHP during Well Bean up

$Production\ rate\ Q = 121.16 * EAVR + 800$ ………………………….Equation 10.1

So, for model 3 we can estimate its EAVR using the FBHP, FTHP and Reservoir depth as 4.1°. Using equation 10.1 which is the inflow system SDM and the calculated EAVR we can estimate that the flowrate for model 3 bean up case as 1300 bpd and this is very close to the 1350bpd prediction in 2016.

10.3 Reservoir pressure effect on well production using EAVR.

One of the principal objectives of production surveillance engineering is continuous monitoring of production assets: data acquisition; performance modelling; issues identification and remedial activity planning for production gains. Some of the well specific production issues include water production, preferential gas production for oil wells, sand production from sandstone reservoirs. There are also facilities related production issues like understanding changes to the well's production envelope and realigning affected wells to more suitable facilities.

Well tests and flowing bottom hole pressure (FBHP) surveys are therefore regularly obtained for continuous production optimization. Some tests from a well with declining performance due to reducing reservoir pressure and increasing water cut are shown in table 12 and an attempt is made to test this actual well performance with the proposed EAVR method.

Table 12. Production well test data.

	Test 1	Test 2	Test 3	Test 4
Test Date	**Feb 2019**	**Nov 2019**	**Jan 2020**	**Mar 2020**
Flowrate (bpd)	**1288**	**903**	**701**	**687**
FTHP (psi)	**690**	**551**	**512**	**490**
FBHP (psi)	**3310**	**3022**	**2883**	**2856**
Reservoir Dept (ftss)	**8520**	**8520**	**8520**	**8520**

Using the February 2019 data (in red fonts) as a baseline we can compute the respective EAVRs for the various test dates as shown in table 13.

Table 13. EAVR calculation from well test data.

Test data	tan(α)	tan(β)	tan(α)-tan(β)	1+tan(α)tan(β)	(tan(α)-tan(β))/(1+tan(α)tan(β))	θ
Test 1	**-0.307512**	**-0.307512**	**0.000000**	**1.000000**	**0.000000**	**0.000000**
Test 2	**-0.307512**	**-0.290023**	**-0.017488**	**1.005072**	**-0.017400**	**-0.996847**
Test 3	**-0.307512**	**-0.278286**	**-0.029225**	**1.008133**	**-0.028990**	**-1.660516**
Test 4	**-0.307512**	**-0.277700**	**-0.029812**	**1.008279**	**-0.029567**	**-1.693595**

Test 1 is used as a baseline and all EAVR were calculated with respect to it and the relationship between the flowrates and the EAVR is as shown in figure 65.

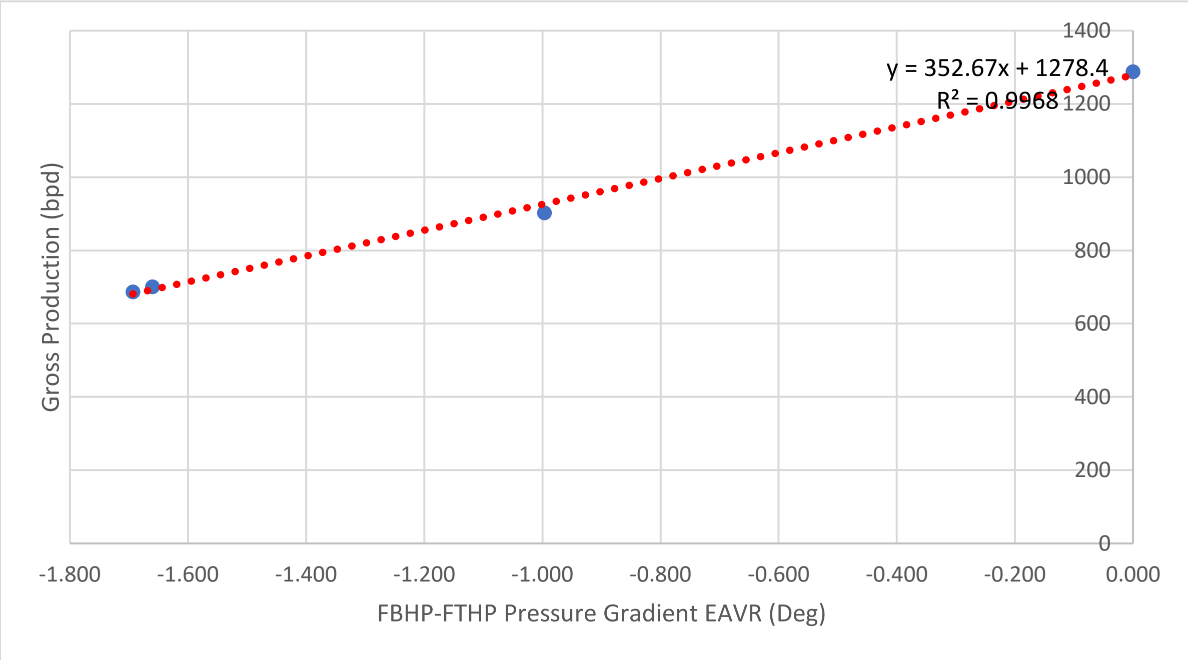


Figure 65. Well test system descriptive model.

The flow equation for this example can be written as

$$Production\ rate\ Q = 352.67 * EAVR + 1278.4$$

This case analysis shows that the reservoir energy loss effect on well productivity can also be analyzed using the EAVR method. One should however note that that at bubble point pressure gas liberation starts and this could affect the application of this concept. The four test points are almost perfectly matched as shown in figure 65 with R^2 of 0.997.

Table 14 compares the actual flow rates with the predictions using the EAVR method. The maximum error from this post-leak data diagnostic method using the EAVR method was less than 3 %.

Table 14. EAVR prediction vs actual flow data.

	Test 1	Test 2	Test 3	Test 4
Test Date	**Feb-19**	**Nov-19**	**Jan-20**	**Mar-20**
Flowrate (bpd)	**1288**	**903**	**701**	**687**
EAVR predicted Flowrate (bpd)	**1278**	**927**	**693**	**681**
Percentage error (%)	**-0.75**	**2.64**	**-1.17**	**-0.86**

10.4 Chapter summary

The concept of EAVR was introduced graphically at Pressure gradient vector analysis section and demonstrated on Leak rate determination in multi-leak situation using EAVR section. These additional tests on the capability to extend the use of EAVR process as a universal concept for predicting leak and inflow during fluid evacuation in conduits is now proven and therefore recommended as part of the smart process for pipeline integrity monitoring.

11 CONCLUSIONS AND RECOMENDATIONS

11.1 Proposed smart process for pipeline integrity monitoring.

The objective of this research was to recommend an improved process for detecting pipeline leak or crude oil theft as well as the quantification of such leak rates. The current reactive use of helicopter overflies which usually kicks off once an unacceptable reconciliation factor is recorded is risky, inefficient, and lagging in response. Technologies capable of addressing research objective like fiscal reconciliation; corrosion monitoring; flow simulation; smart field operation; fiber optic sensing; frequency response function modelling using acoustics or vibration and floating micro robots were reviewed for possible leads for the design of an improved process for leak detection. Smart operations technology based on strengths and weakness analysis exercise came out as the preferred technology for the proposed new process. Smart fields operation uses artificial intelligence workflow to partially perform human tasks aimed at reducing the decision cycle time for data-based decisions as well as managing production data uncertainties. The artificial intelligence operation domain is huge and varied hence some further study was undertaken to find which aspects of smart operations would be found more suitable for the achievement of this research objective of leak detection and leak rate quantification.

A hypothesis or an axiom are basically like two sides of the same coin in the Pragmativists philosophy and were evaluated for the conceptualisation of suitable approaches to smart operation process for analysing production data trends for leak detection and quantification. The production data analysis would be in the form of trend monitoring such that any deviation from anticipated or established trends could be used to detect leak or crude oil theft. A pragmativist philosophy was applied to test the hypothesis that “If we have a way of continuously measuring the steady state conditions at regular intervals (say 5 or 10km) of a given pipeline during operation, then we could, through deviations trending from the steady state operation, determine the point of leak or crude oil theft and quantify leak rate or theft". The use of axioms was also tested, for the realisation of documented research objective, using cause and effect relationship or artificial neural network during pipeline crude evacuation such that deviations from known data trends could be used for the determination of leak or crude oil theft. These two data driven smart operations workflows were evaluated for framing a new process for pipeline integrity monitoring. Machine Learning workflow was introduced as an optimisation process that could be applied to improve results from these two data driven smart operation workflows.

One approach to designing a data based smart process in pipeline transport process, based on use of deductive reasoning on pragmatist epistemology, would be to start with a hypothesis and then test such hypothesis using observed data to see if observed data follow some trends as proposed in the hypothesis. Another smart operations approach based on the same pragmatist epistemology would be to concentrate on observable data and use some axioms to form an explanatory model of the observed data. This later approach is based on inductive reasoning. The main difference between these two knowledge systems is that one is based on immediately acquired (post-leak data diagnostic process) data from the pipeline being investigated while the other is based on past (pre-leak data prognostic process) environmental data from the pipeline being investigated or similar pipeline in the past.

In pre-leak data prognostic process methodology, the analysis focuses on events that could be assessed to have happened before a particular outcome or result is achieved. For example, you need to have punctured a pipeline before a leak could be established. In post-leak data diagnostic process (immediately acquired data) methodology we focus on current results to determine the preceding events. Applying post-leak data diagnostic process methodology, on the same example above, we could say that if there is a leak on a pipeline it means that the pipeline must have been punctured. An attempt was made to process available data through an SDM model for testing both the conceptualised pre-leak data prognostic process and post-leak data diagnostic process. Post-leak diagnostic processing is instantaneous, instrument based, and requires that we have some knowledge of what is flowing while pre-leak prognostic processing is based on past data events surrounding the pipeline being investigated or a similar pipeline that have been subjected to the same situation being investigated. The data-based events which influence pipeline leak, based on pre-leak processing are difficult to generate in the Niger Delta and hence makes the use of pre-leak prognostic processing methodology difficult. Post-leak diagnostic process analysis methodology seemed promising since it is based on measurements. However, the current process of data acquisition practice in Niger delta, where only three-point data acquisition system is used, limits the level of accuracy achievable with available post-leak diagnostic processed data methodology. This therefore necessitated a further study to reprocess the available data to the required intensity for the application of post-leak data diagnostic processing.

Computer simulation, instead of rig-based laboratory experiments, was chosen for this data reprocessing exercise based on cost and time resource requirement. Some of the applicable robust software for such simulation based on reviews include: PIPESIM; Surfer; Aspen HYSYS; myQuorum; CHEMCAD; PIPEPHASE; Petro-SIM and ATMOS. These software are expensive but research versions of most of them could be received in support of academic research. PIPESIM which ranks among the best was chosen based on personal knowledge. A donation request was made to Schlumberger UK and a research version of the PIPESIM software was donated to DMU in support of this research. Several sets of experiments were simulated in PIPESIM and the output data corresponding to respective input data has been collected, investigated, and analysed. The conclusions of preceding experiments most times were used to frame the next set of experiments and this cycle continued until the end of this research. The actual leak or crude oil theft rate is determined by the difference between the sum of what is pumped through the system and that which is received at the terminal. This difference is monitored regularly as terminal reconciliation factors. The PIPESIM simulation results were analysed for pressure variations at selected pressure monitoring points. The first investigation was based on transmission pressure differential at such monitoring points. Observed results turned out to be encouraging and showed that one could generate infinite realisation of leak failures for the same pipeline that could be used in single leak prediction evaluation.

The theoretical basis for the use of pressure gradient for leak detection was also discussed as a practice worth replication from subsurface reservoir engineering workflow. This study was based on two analogous comparison to subsurface reservoir engineering practice of using fluid pressure gradients to determine fluid contact planes as well as the use of pressure decline to determine the total fluid produced from a well-defined subsurface hydrocarbon reservoir. This leak monitoring results from the use of fluid pressure gradient yielded an improvement over those from the use of pressure differential for pipeline leak detection. A further study on the relationship between volume flow rate and pressure gradient in pipes for steady state incompressible fluid was conducted. PIPESIM simulation results agree with the volume flow rate and pressure gradient relationship derived from a solution of the Navier stokes equation. This agreement was taken as a validation of the robustness of PIPESIM simulation software as well as a calibration to the simulation models created in this study.

Having verified the robustness of the PIPESIM models, the use of two analytical methods for estimating multiple leaks in any pipeline evacuation system were further studied. These analytical methods built on the use of pressure gradient which has already been proven. The results demonstrated that the use of gradient method is effective in multiple leaks detection in any pipeline system but would need additional work to be able to assign the leak rates to the respective leak points. The concept of pressure gradient relaxation (PGR) was introduced and demonstrated through some vector manipulation which showed that the transmission pressure gradient vector remains a constant until the onset of leak or theft which leads to a relaxation of the transmission pressure gradient. This PGR concept was used to progress another set of experiments for leak rate estimation. The results from this set of experiments reveals that the leak rate in a single leak situation could be precisely estimated using the PGR method. This successful result led to the postulation that it is possible to combine the gradient line intersection method and the PGR method to identify and quantify multiple leaks in any given pipeline system. This PGR approach was also investigated for estimating the leak position and leak rate in multi-leak situation. This involved step by step estimation of leak rate by comparing the volume flow rate and their respective PGRs. Starting from the inlet where we know what is flowing and what pressure gradient it could generate, the leak rate at each section of the pipeline could be step wisely calculated from inlet to discharge point. This option did not yield reliable results beyond a two-leak situation and hence could not be progressed further. Some further research was therefore needed to progress the use of PGR method beyond a two-leak system as the assumption of uniform flow constant K becomes unsustainable after the second leak.

The enclosed angular vector relaxation (EAVR) method was used for multiple leak rate estimation and the results from this approach were impressive. Every pipeline used for fluid evacuation has a pipeline leak characteristic curve which is the anticipated transmission pressure without a leak and how such curve changes with leak. The computation of pipeline leak characteristic curve is therefore recommended as a standard procedure during pipeline commissioning so that the recommended smart process for pipeline integrity monitoring from this research can be applied for integrity monitoring of such pipeline. This curve can be used to document the pipeline system descriptive model when plotted against some simulated EAVRs due to leak. This SDM, once developed can be used to predict leak rate for the given pipeline. This new process was tested using three case studies and the results from this approach were outstanding for multiple leak investigation, hence the use of EAVR process was adopted for leak rate and inflow rate quantification in the recommended smart process for pipeline integrity monitoring.

11.2 Discussion

Two analytical methods, which uses the pipeline pressure gradient as a basis, were independently verified in leak point and leak rate estimation. While the use of graphical gradient line intersection method has the capability for multiple leak identification, the results from such prediction could be used to respectively calculate the corresponding leak rate for the identified leak points using the enclosed angle vector relaxation.

The system descriptive model (SDM) earlier introduced in chapter 5 page 104 is now recommended as a necessity for the implementation of the propose new smart process for pipeline integrity monitoring. This pipeline SDM was developed as a graph or an equation that describes the pipeline pressure response relaxation angle as a function of the leak that could create it. The pipeline pressure relaxation angle itself is based on pipeline leak characteristic curve which is now recommended to be acquired for any pipeline operating system as a prerequisite for leak monitoring in any pipeline using this recommended smart process for pipeline integrity monitoring. The pipeline leak characteristic curve is a plot of pipeline during normal operation without a leak and how such pipeline would behave through its pressure response with some simulated leak.

The results from this approach were outstanding for multiple leak investigation and hence the use of EAVR process was adopted for the recommended post-leak data diagnostic smart process for pipeline integrity monitoring. This EAVR approach is unique, very simple, and has not been applied before nor documented in any fluid transport literature for leak identification and estimation.

It has become important to distinguish between the technologies reviewed in chapter 3 on LITERATURE REVIEW page 55 and the mathematical process involved in the solution suggested by the several authors involved in technology solution relating to leak monitoring and how they contrast to the EAVR solution recommended in this dissertation. This research process involved deductive reasoning which starts with a hypothesis then the analysis of hypothesis for confirmation. The leak detection taxonomy discussed in section 3.3 on Technology preselection review page 60 addressed all the technologies already applied or have the capacity for application in leak detection. Most of these technologies were reviewed for potential application. The technology application in this research is pressure monitoring and the process for the use of this pressure monitoring using vectors is part of the novelty of this work. The use of pressure monitoring has been researched by several authors (Ben-Mansour et al., 2012; da Silva et al., 2005; Feng & Zhang, 2004; Gong et al., 2014; Jin et al., 2014; Kim & Lee, 2009; P. J. Lee et al., 2005; S. Li et al., 2014, 2016; Liu et al., 2019; Murvay & Silea, 2012; Mysorewala et al., 2015; Omodanisi et al., 2009; Ostapkowicz, 2016; Rojas & Verde, 2020; Verde, 2005; Zhang et al., 2009)

The basis for the leak detection in most of these studies are either pressure and volume direct measurements or based on indirect measurement of the effect of these parameters. These indirect effects are either based on pressure pulses, waves, or vibration due to leak. Some of these researchers also used pressure gradient monitoring but the process for locating leak points is different from the outcome of this research.

Feng and Zhang (2004) concluded that double sensor pressure gradient method together with a flow difference and pressure detection method, for detecting and locating leak in oil pipeline using only measurements at the ends of the duct. Their work is very simplistic and involved a set of experiments using four pressure sensors (two on each side of simulated leak) to locate simulated leak point on the pipeline. This work should be considered as another way of evaluating the results of sections 9.2 on Gradient intersection method for leak point detection as documented on page 174 of this thesis. One shortcoming from their work is that it did not go beyond locating a single leak and neither was it framed to quantify leak rate.

Jin et al., (2014) describes an integrated model implementation of leak detection and location that can be used for background leakages in liquid pipelines. Their approach includes a dynamic monitoring module (DMM) and static testing module (STM). The DMM can detect larger leakages of background ones using the amplitude propagation and attenuation model of pressure waves. This experimental work is based on a large water distribution rig and uses the STM, based on the pressure loss model, can detect micro-leakages, which is an effective compensation for the DMM. Their results show that the integrated model can detect nearly all leakages but was not designed to quantify the leak rate.

Ben-Mansour et al., (2012) studied some computational fluid dynamic (CFD) simulation of small leaks in a pipe having 0.1 m diameter using a 3D turbulent flow model in a CFD simulation and tested their results experimentally. Their steady state simulations showed clear leak signatures in the pressure and pressure gradient variations along the pipe. Their work showed that the presence of a leak causes measurable differences in the magnitude and frequency of the pressure signal spectrum and also in the averaged power spectral density

(PSD) for the range of 220–500 Hz frequency. Their simulations showed clear influence of the leak on the pressure gradient along the different paths of the flow inside the pipe. For very small leaks (below 1 liter/min), this influence is not very strong in the pressure signal, but very clear in the pressure gradient. The results also indicate much influence of the line pressure and leak size on the leak flow rate. The results show that the leak causes clear increase in the magnitude and frequency of the pressure signal spectrum and also in the averaged PSD for the range of 220–500 Hz frequency. Based on these results, an experimental setup has been designed and built to verify the above findings using dynamic pressure transducers. Both the numerical and experimental findings were part of a research project aimed at designing reliable and robust methods for detecting leaks in water pipeline networks in city underground. It should be noted that the objective of this research is about monitoring crude theft. Crude theft is a redirection of some flow to the theft conduit and so the use of frequency monitoring due to leak, as recommended by Ben-Mansour et al., (2012) does not arise. However, the finding that there is a very clear signature in the pressure gradient even for very small leaks is germane.

The most current related leak detection research was documented by Rojas & Verde (2020) These researchers relied heavily on instruments, most of which have been discounted as inapplicable in oilfield pipeline systems. J. Rojas, & C. Verde (2020) concluded, as documented here, that a precise knowledge of the hydraulic gradient is required if leaks must be located. A comprehensive review of pipeline leak research from 2003 to 2017 was undertaken by Rojas & Verde (2020) as a justification of their 2020 work on the design of an accurate location scheme for sequential leaks. According to them: "One adaptive observer, according to Besançon (2007), is applied only for identifying the parameters of the hydraulic gradient during the detection stage, and the second observer estimates the equivalent leak position and its piezometric head by assuming that the parameter of the hydraulic gradient is constant during the leak location time. An extended Kalman filter (EKF) or a Sliding Mode

Observer (SMO) are suggested for the second observer. Thus, one observer calculates the slow deviations of the hydraulic gradient when the residual is off, and the other observer precisely locates the equivalent leak position by using the loss function previously estimated." Verde and Rojas considered transient flow model and their real-time experiment is carried out with a constant upstream pressure and the downstream atmospheric discharged pressure. Their assumed downstream atmospheric discharge pressure conditions could be said to be not quite representative of crude oil pipeline evacuation conditions as described in page 145. Their work is based on wavelets and pressure pulses and were conducted on small pipes in laboratories. The technology employed is similar to acoustics and vibrations which were earlier discounted as inapplicable in very large, buried pipelines as documented in page 82.

There are similarities to the two conclusions from this research and that from Rojas & Verde (2020) even though the two research are based on two different methodologies. The first similarity which is also in agreement with Feng and Zhang (2004) and Ben-Mansour et al., (2012) and others, is that the use of pressure gradient is very vital for leak detection. This research arrived at this conclusion in two stages. First by testing the research hypothesis that leaks can be evaluated through monitoring of pressure trends. Thereafter the practice worth replicating in subsurface reservoir engineering was used to test the usefulness of using pressure gradients in leak detection and that was found to be invaluable. This research did not just prove the necessity for using pressure gradient for leak detection, it demonstrated that through some pressure gradient vector manipulation the effect of leaks on transmission pressure gradient could be evaluated. In principle the onset of leak modifies the original transmission pressure gradient vector, and this modification leads to a resultant vector whose magnitude and direction is different from the original pressure gradient vector. The change in direction of this resultant vector, due to leak, has been defined as enclosed angle vector relaxation and was proven to be invaluable for the quantification of leak rates. This approach, especially the use of EAVR, has not been documented and used for leak detection and leak rate quantification before now. One of the spin offs from this research is a promising lead to further research area for the estimation of the relationship between the flow constants (K) and leak rates causing the modification of the pipeline flow constant. The second similarity between this research and conclusions from Rojas & Verde (2020) is that you need two different processes for the evaluation of leak point and the leak rate estimation. Most researchers used additional instrumentation to evaluate the leak rate, but this research has actually used the same pressure gradient method to calculate the pressure gradient relaxation angle for the determination of leak rate at any identified leak point in any pipeline.

This smart process for pipeline integrity monitoring is unique and capable of predicting leak and quantifying leak rate under suitable conditions as documented below.

11.3 Conditions for the application of proposed new smart process

The following two conditions are necessary and sufficient for the deployment of the proposed new process for pipeline integrity monitoring:

1. That the fluid is single phase, incompressible and irrotational.
2. There are sufficient pressure measurement points at regular intervals along the pipeline length.

The conditions for the particular solution to the Navier stokes equation used in this research, as discussed in Pressure gradient relationship to volume flow rate, are incompressible and irrotational fluids and these are generally the conditions under which the application of the recommended new post-leak data diagnostic smart process will be valid. The validation of these conditions has been proven by experiments but could also be demonstrated using equation 8.1 or explained using the graphic vector manipulation as documented in section on Pressure gradient vector analysis. It should be noted that the fluid pumping operation involve energy transfer from pump energy to kinetic energy of the evacuated fluid and the objective of the crude evacuation is near perfect transfer of all the pump energy for fluid transportation without packing or compression. This therefore means that some energy would be lost if the fluid transported is compressible, hence this recommended approach should not be applicable in gas transportation. Special attention should also be made while applying the EAVR process during the transportation of two-phase fluids, especially at saturated conditions. An example of an equilibrium two phase fluid would be a saturated crude oil where the crude already has the maximum gas in solution at the prevailing condition. A saturated reservoir is one which operates at pressure greater than the bubble-point pressure of the crude oil. This therefore means than care should be taken in the application of this recommended approach in fluid transportation within the well as each molecule of crude that moves from the liquid to the gaseous phase is a source of packing error in the EAVR application of the recommended new process for leak and inflow detection and quantification. Every attempt should also be made to ensure that evacuated fluid is irrotational to ensure validity of the propounded EAVR process. This is achieved as part of the crude evacuation pipeline design as the discharge pressure is preset above atmospheric such that the pipeline is completely filled and pressured before the first discharge is received at the terminal.

Another potential limitation to the application of this proposed new process for pipeline integrity monitoring would be the available number of pressure monitoring points as they are critical for accurate prediction of leak point and rate. With this process dependency, it would be advisable to always use any repair opportunity on any pipeline during operational maintenance to install new pressure monitoring points on existing lines. The monitoring of a 100km trunkline, for example, through pressure measurements at three manifold points is suboptimal. This recommended new way of working could also be used to revise pipeline installation standards, especially in Nigeria or similar jurisdictions where vandals would attempt to hot tap and steal crude or any fluid being transported through pipelines. Such improvements in standards would include recommendation for pressure monitoring point installation at suitably agreed regular intervals during any new pipeline installation and the implementation of pipeline IoT architecture as highlighted in Pipeline digital information data acquisition system.

11.4 New process for pipeline integrity monitoring

A key word in process engineering is the organization of particular steps, or procedures, for the achievement of a given objective. Using our common example of electromagnetism, we could demonstrate that having a conductor coil, an iron core and an electric source does not produce an electromagnet until the iron core is enclosed by the coil which is energized with some current. So, the new process for pipeline integrity monitoring involves some new way of executing some existing activities while incorporating the newly proven concept of EAVR for leak rate estimation.

A new two staged process for leak monitoring during crude evacuation process has been conceptualized through a hypothesis, tested using pipeline transmission pressure data, and verified using the EAVR to prove that the pipeline pressure gradient vector changes according to leak rate. The testing and demonstration process involve a philosophical vector manipulation of how the pre-leak vector gradient will change to a new vector once there is a leak. The direction of this new vector is different form the direction of the pre-leak vector and this gives rise to the enclosed angle vector relaxation. This research process, as documented in Research method which gave rise to a research hypothesis states that: If we have a way of continuously measuring the steady state conditions at regular intervals (say 5km or 10km) of a given pipeline during operation, then we could through deviations trending from the steady state operation determine the point of leak or crude oil theft and quantify leak rate or theft, has been verified. The search for this new concept was driven by literature review which suggested the use of some smart operation ideas in the new process design. As documented in the section Smart fields operations synopsis the basis for smart fields operations and digital twin is simulation and there are several levels of smartness or smart operations capability. The first step in this new process uses a graphical gradient line intersection method for multiple leak identification, while pressure gradient relaxation angle is applied at the identified leak points to determine the precise leak rate at each identified leak point. The concept of pipeline system descriptive model was created to represent the performance of a pipeline without leak as well as for the prediction of how such pipeline would behave at different leak rates. The results from this approach were outstanding for multiple leak investigation. This approach is very precise on leak location prediction and leak rate estimation at the respective leak positions. Some of the value adds for this new process includes simplicity, ease of operations, retrofit ability to existing pipeline, and basic knowledge skill requirement for operational staff.

The new process is based purely on pressure measurements and some knowledge of basic pipeline design data like lengths and diameters. The pipeline basic design data are always readily available as part of operational emergency response preparedness data requirement. Pressure monitoring is part of normal operations during crude evacuation process so this proposed new process would not demand changes to operational requirements nor some form of skills reassessment for operators prior to deployment. The number of measurement points at any given pipeline would however need to be increased if the desired level of accuracy achievable by this process would be realized in the given pipeline. Most operations already use some form of SCADA systems that allows the transmission of pressure reading directly through global IT system to the point of need. This is necessary as simultaneous reading of all installed pressure monitors are necessary for this new process, and indeed for all processes that are capable of multiple leak detection. There is no need for expertise training on simulation, nor differential equation evaluation expertise capability for the application of this new process. An apparent difficult problem of hydraulic simulation has been studied and reduced to a simple solution requiring the measurement of pressures and some basic pipeline configuration background knowledge. What is required for the application of this new process is ability to update a workbook, manually or automatically, with readings of the installed pressure gauges, the plotting of such data (manually or automatically) to determine the points of leak. And thereafter using the leak points to determine, manually or automatically, leak rate at each leak point. This new process met the desired Research objectives and the documented criteria in the concept selection report.

In summary, a SMART PROCESS FOR PIPELINE INTEGRITY MONITORING involving: data acquisition; data baselining; leak point determination and leak rate determination has been developed and proven as capable of detecting multiple leaks (and inflows) and quantification of the respective leak (and inflow) rates at the identified leak points.

11.4.1 *Data acquisition strategy*

This enabling step involves background check on the pipeline being investigated for ability to acquire the required pressure data from available pressure monitoring points and validation of the adequacy of the number of pressure monitoring points for planned use of proposed new process for leak detection. It should be noted that results from the new process are precise so long as the identified leak is in between two monitoring points. The available number of pressure monitoring points therefore determine the accuracy of multiple leak detection points as discussed in Conditions for the application of proposed new smart process page 225. As part of new process implementation, this recommended new way of working could therefore be used to revise pipeline installation standards, especially in Nigeria such that the applicable construction standards could be updated to recommend pressure monitoring point installation at suitably agreed regular intervals during any new pipeline installation. It is also hoped that as part of the future way of working, new pipelines would be equipped with real time data acquisition infrastructure.

11.4.2 *Data baselining*

This involves pressure gradient estimation without leak and the determination of the pipeline leak characteristics and documentation of the pipelines system descriptive model (SDM). This SDM could be considered and evaluated as part of the commissioning data during any new pipeline installation or during any repair opportunity for existing pipeline. The SDM process testing involves the documentation of pipeline pressure response without a leak and some response under simulated leak situation. The pressure gradient estimation without leak should be evaluated at rates around the designed operating rate for the given pipeline being investigated. A good knowledge of the pressure gradient for any two volumes around the normal pipeline operating volume would be advisable as the relationship between pressure gradient and flow rate has been proven to be a straight line. This means that any SDM created for a given pipeline could be used to cover all operating domains through interpolation or extrapolation to any unexplored volume. This SDM is the required nomogram to estimate the leak rate (or inflow) at any section of the pipeline during any operational leak.

11.4.3 *Leak point(s) determination*

This involves plotting of pressure readings for the determination of leak points. For pipelines with installed SCADA systems, an algorithm could be created for sampling and filtering of the pressure data stream at regular intervals and use same to plot the pressure trend, track deviation from straightness and use that to show points of leak. Where such SCADA systems do not exist then some manual intervention would be used to plot and determine points of leaks.

11.4.4 *Leak rate determination*

This involves the use of the evaluated points of leak to estimate the leak rate at each identified leak section using the pipeline leak characteristic curve or the SDM already computed as part of the pipeline commissioning data as described in Data baselining. The pipeline leak SDM is a plot of leak rate versus pipeline anticipated enclosed angle vector relaxation (EAVR) due to leak. The respective pressure gradients during leak monitoring would be used to estimate their corresponding EAVR which will then be used on the SDM to evaluate the respective leak rates at identified leak points.

11.5 New process novelty

Discovery, which is the process of being discovered must be distinguished from invention which is the act of inventing a product or a process. So, in effect we discover something that exists without general latent knowledge, but we invent a product or a process that is new and sometimes novel. The documentation of Hydrogen as part of naturally occurring elements in the periodic table is a discovery, but the use of the same Hydrogen under certain condition to create a hydrogen bomb is a product invention. This implies that knowledge from discoveries can be used for inventions as shown in the above example of Hydrogen as one of the naturally occurring elements in the periodic table and the use of such hydrogen in the invention of a hydrogen (or thermonuclear) bomb. Also, electricity is an invention which is a product of the discovery of static electric charges. Electromagnetism has been used severally in this thesis as a process invention example. Surgical operating procedures is also another example of process invention which is continuously being updated with new data in medical sciences to continuously improve on Medicare.

The EAVR delivered as part of this research is a process invention: It is novel, a product of this dissertation and not conceptually documented in any literature.

The details of this new smart process for pipeline integrity monitoring knowledge contribution based on this dissertation are:

1. The thought of using vectors to analyze pressure gradient changes during fluid evacuation for leak identification is novel and a process invention.
2. The use of structural analogues to describe fluid evacuation and hence help in the post-leak data pressure gradient vector analysis during fluid evacuation process is also a novel discovery.
3. The combination of 1 and 2 above gave rise to the EAVR concept for leak rate (or inflow) estimation in any pipeline fluid evacuation system is the main product of this research and is germanely a novel invention.

The EAVR concept, which is one of the main contributions of this research is a new knowledge addition to physis and fluid mechanics. The EAVR is also a discovery, just the same way as Sir Isaac Newton discovered the gravitational force which has always been with man.
In conclusion therefore, the EAVR process which is a new discovery uses the vector analysis discovery to develop an EAVR process invention.

11.6 Chapter summary

The main conclusions from this research are:

1. Demonstration of research hypothesis using pipeline pressure transmission data.
2. Demonstration of leak prediction accuracy dependency on the number of pressure monitoring points.
3. Demonstration of a novel vector analysis approach for monitoring of leaks.
4. Demonstration that the research product, which was developed for leak monitoring can also be extended for inflow monitoring.

The thesis hypothesis, which propounded that "if we have a way of continuously measuring the steady state conditions at regular intervals (say 5km or 10km) on a pipeline during operation, then we could, through deviations trending from the steady state operation, determine the point of leak or crude oil theft and quantify leak rate or theft," was supported and indeed leak rates can be detected and quantified through pressure measurements only. The confirmatory use of this process yielded exceptional average prediction accuracy of 93.44% as can be calculated from table 15.

Table 15. Predictions from proposed new smart process for pipeline integrity monitoring.

Case	Description	Number of predictions	Average prediction accuracy
1	PIPESIM multi-leak simulation	8	89.97%
2	Well inflow and choke performance prediction	1	96.29%
3	Reservoir pressure effect on well production	4	99.68%

The use of the recommended new process builds on pressure gradient calculations hence it was also concluded that the accuracy of this new process for pipeline integrity monitoring would largely depend on the available number of pressure monitoring points. With this process dependency, it was therefore recommended that one way of retrofitting this new process on existing pipelines would be to always use any repair opportunity on any pipeline during operational maintenance to install new pressure monitoring points.

Another conclusion from this research was the successful outcome of using vectors to analyze pressure gradient changes (caused by leak or crude theft) during fluid evacuation for leak identification. This approach is novel and a process invention and yielded good results that led to the achievement of the research objective of leak and crude oil theft detection during pipeline crude evacuation using the post-leak data diagnostic smart operations process.

A combination of this novel pressure gradient vector analysis and another, out of the box thought, on using structural analogues to describe fluid evacuation helped in the post-leak data diagnostic smart process for pipeline integrity monitoring. The pressure gradient vector analysis during fluid evacuation process and the construction of the enclosed angle vector relaxation for the delivery of a new smart process for pipeline integrity monitoring has been demonstrated and recommended. This recommended smart process for pipeline integrity monitoring is based on PGR for leak point determination and EAVR for leak rate estimation. Although some researchers have recommended the use of pressure gradient monitoring for leak point determination, the approach presented here that led to the same conclusion is different. The concept of enclosed angle vector relaxation method for leak rate estimation which is recommended in this research is new and has not been published in any leak prediction literature**.** Some of the advantages of this new process is simplicity, retrofit ability and no demand for skills reassessment for operators as it fits into normal operations. This finding would be particularly useful to pipeline operators in Nigeria or similar jurisdictions where vandals would attempt to hot tap and steal crude or any fluid being transported through pipelines. The EAVR concept, which is one of the main contributions of this research is a new knowledge addition to physis and fluid mechanics.

In the graphical proof of concept documented at Pressure gradient vector analysis it was felt that this EAVR can also be used to estimate fluid inflow in addition to leaks. This is because the difference between inflow and leak is that one is opposite of the other in sign convention within the domain space being studied. This corollary was tested through two case studies in subsurface engineering. The results of the two tests, as shown in table 15 (case 2 & 3) can be compounded to yield an average of 99% prediction accuracy.

In conclusion therefore, the EAVR process which is a new discovery in science (physics and fluid mechanics) uses the vector analysis discovery to develop an EAVR process invention.

11.7 Further research

This new process for pipeline Integrity monitoring could be implemented manually, semi automatically, or completely automatic, based on artificial intelligent workflow depending on the available IoT infrastructure. A computer program for the development of this concept could be subject for further research. Also, further advancement of the recommended new process using machine learning operations could also be another enhancement area for further research.

Another possible spin off from this research would be a further research on the relationship between the flow parameters of a leaking pipeline system. It is believed that the same PGR method could be used to constrain the Navier Stokes solution for the determination of the respective sectional pressure gradient after a leak and the corresponding remaining fluid quantity after the leak. This relationship was tested as part of PGR method for leak rate evaluation in multi leak situation but the error in the leak rate estimation beyond the second leak was unacceptable, based on computing assumptions as documented in Leak rate determination in multi-leak situation using PGR .

A third potential further research area would be the design of methods for data generation and modeling of **Hidden Layers**, page 124, for the creation of an SDM for use of pre-leak data prognostic artificial neural network methodology for trunkline leak detection.

11.8 APPENDIX *I*. Particular solution to Navier Stokes equation (Ugaz, 2020)

Re. Figure 45.

Since the flow is in the z direction $u_r = u_\theta = 0$

Therefore, all the r and $\theta\ derivatives\ of\ the$ Navier Stokes equation are therefore zeros.

The LHS of the Z component is also zero because of steady state assumption so the z component of the Navier Stokes equation yields

$$0 = -\frac{\partial P}{\partial z} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)\right]$$

$$\frac{\partial P}{\partial z} = \frac{\mu}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)$$

But $\frac{\partial P}{\partial z} =-\frac{\Delta P}{L}$

$$\frac{\partial P}{\partial z} = \frac{\mu}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)$$

The above is a second order differential equation and with its boundary conditions could be solved by integration.

$$-\frac{r}{\mu}\frac{\Delta P}{L} = \frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)$$

$$\int \frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right) = -\int \frac{r}{\mu}\frac{\Delta P}{L}$$

$$r\frac{\partial u_z}{\partial r} = -\frac{r^2}{2\mu}\frac{\Delta P}{L} + C_1$$

$$\int \frac{\partial u_z}{\partial r} = -\int \left(\frac{r}{2\mu}\frac{\Delta P}{L} + \frac{C_1}{r}\right)$$

$$u_z = -\frac{r^2}{4\mu}\frac{\Delta P}{L} + C_1 ln(r) + C_2$$

Applying the boundary condition @ r=a $u_z = 0$ and at r=0 u_z *is a positive number*

Yields
$C_2 = \frac{a^2}{4\mu}\frac{\Delta P}{L}$ and $C_1 = 0$

This implies

$$u_z = -\frac{r^2}{4\mu}\frac{\Delta P}{L} + \frac{a^2}{4\mu}\frac{\Delta P}{L}$$

$$u_z = \frac{a^2}{4\mu}\frac{\Delta P}{L}\left(1 - \frac{r^2}{a^2}\right)$$

Therefore, Volume flow rate

$$V = \int u_z \, dA$$

But dA=2πrdr, so

$$V = \int_0^a \frac{a^2}{4\mu}\frac{\Delta P}{L}\left(1 - \frac{r^2}{a^2}\right) 2\pi r dr$$

$$= \frac{\pi a^2}{2\mu}\frac{\Delta P}{L}\int_0^a \left(r - \frac{r^3}{a^2}\right) dr$$

$$= \frac{\pi a^2}{2\mu}\frac{\Delta P}{L}\left[\frac{r^2}{2} - \frac{r^4}{4a^2}\right]^a$$

If a=r, then the volume flow through the pipe cross section If a=r, then the volume flow through the pipe cross section

$$V = \frac{\pi a^4}{8\mu}\frac{\Delta P}{L} \qquad \text{8.1}$$

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