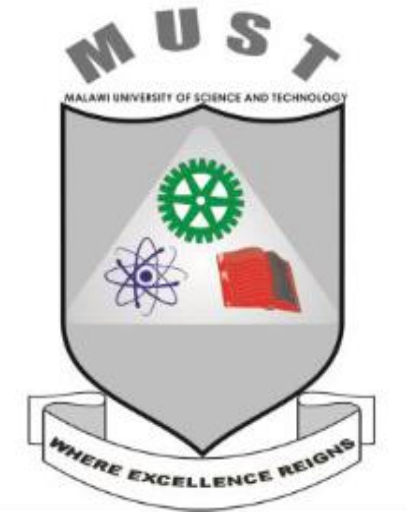


INVESTIGATING THE EFFECTS OF CORROSION IN THE DOWNSTREAM SECTOR OF MALAWI'S PETROLEUM INDUSTRY

MIRACLE PHOMBEYA (PRE/017/19)

THYOLO, MALAWI

Dissertation submitted to Ndata school of Climate and Earth Sciences of the Malawi University of Science and Technology in partial fulfillment of the requirements of the Bachelor of Science degree in Petroleum Geosciences (Oil and Gas).

10th November, 2023

DISSERTATION APPROVED BY:

SUPERVISOR:

Mr. Wilson Tchongwe Signature: 

ASSESSOR: Signature:_____

DISCLAIMER

This document describes work undertaken as part of a program of study at Ndata school of Climate and Earth Sciences at the Malawi University of Science and Technology. All views and opinions expressed therein remain the sole responsibility of the author(s), and do not necessarily represent those of the school.

COPYRIGHT STATEMENT

This copy of the dissertation has been supplied on condition that anyone who consults it is understood to recognize that its copyright rests with its author and that no quotation from the dissertation and no information derived from it may be published without acknowledgement.

ABSTRACT

The focus of this research was on investigating the various effects of the different mechanisms of corrosion present in the downstream sector of the petroleum sector of Malawi for the purpose of with the goal of improving the performance and reliability of equipment and infrastructure. The study was carried out with the specific objectives of: assessing the specific causes of corrosion in the downstream sector of the petroleum industry, identifying the different types of mechanisms of corrosion occurring in the industry as well as their effects and finally, the mitigation techniques currently being applied by the industry.

As for the research design, a mixed-methods approach was adopted, combining quantitative and qualitative methods of data collection (Tegan, 2021). This approach allowed a comprehensive and more in-depth understanding of the research topic by combining the strengths of both quantitative and qualitative research. The quantitative methods involved were the collection of quantitative data on corrosion incidents of the past and their effects in the industry. The qualitative methods employed, on the other hand, were collecting non-numerical data which were interviewing the employees of NOCMA and Total as well as credible personnel and observations on the conditions of storage and transportation tankers. These methods provided rich and contextual insights into people's experiences, perspectives, and beliefs. In this research, interviews with industry experts and maintenance personnel were conducted to gather insight on corrosion causes and mechanisms on storage and transportation tanks in Malawi, their impacts, and suggestions for improvement.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude and appreciation to all those who have contributed to this research till its completion.

First and foremost, I would like to express my humblest gratitude to the Almighty God for letting me live to the completion of this study.

I am also immensely thankful to my supervisor, Mr. Wilson Tchongwe, for his support, guidance, and invaluable insights throughout the research process. His mentorship has been instrumental in shaping this dissertation and has pushed me to try my hardest to satisfy all needs of this research.

I would like to extend my heartfelt thanks to my family of Mr. and Mrs. Phombeya, including my brother and sister for their support in my abilities and their constant encouragement. Their love and support has brought this far.

My sincere appreciation goes to my friends and colleagues who provided moral support and academic support as well. Their kind acts kept me motivated during challenging times.

I am also grateful to the participants of this study whose willingness to share their experiences and insights made this research possible.

Finally, I want to acknowledge the invaluable resources and facilities provided by Malawi University of Science and Technology such as the free internet and consent letters. These resources have been crucial in conducting my research effectively.

This dissertation would not have been possible without the collective support and encouragement of all these individuals and institutions. Thank you for being a part of this significant milestone in my academic journey.

Contents

ACRONYMS/ABBREVIATIONS i
LIST OF FIGURES ii
LIST OF TABLES iii
CHAPTER 1: INTRODUCTION 1
Background 1
Problem Statement 2
Main and Specific Objectives 2
Research Questions 3
Significance of the Study 3
CHAPTER 2: LITERATURE REVIEW 4
Materials for constructing the infrastructures for storage and transporting petroleum products 4
Causes of corrosion in the downstream sector of the petroleum industry 5
Types of Corrosion/ Corrosion mechanisms 7
CHAPTER 3: METHODOLOGY 13
Research Design 13
CHAPTER 4: RESULTS AND DISCUSSION 18
1. Qualitative data 18
2. Quantitative data 20
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS 23
CONCLUSION 23
RECOMMENDATIONS 23
References 27

ACRONYMS/ABBREVIATIONS

APB	:	Acid Producing Bacteria
Cl-	:	Chloride ions
CSCC	:	Chloride Stress Corrosion Cracking
HIC	:	Hydrogen Induced Cracking
H_2S	:	Hydrogen sulfide
IOB	:	Iron Reducing Bacteria
MA	:	Methanogenic Bacteria
MIC	:	Microbiologically Influenced Corrosion
NDT	:	Non-Destructive Technique
NOCMA	:	National Oil Company of Malawi
SCC	:	Stress Cracking Corrosion
SFRs	:	Strategic Fuel Reserves
SRB	:	Sulfate Reducing Bacteria
SSC	:	Sulfide Stress Cracking

LIST OF FIGURES

Figure 1: Shows Uniform corrosion in carbon steel

Figure 2: Shows Pitting corrosion in carbon steel

Figure 3: Shows Crevice corrosion in a steel tanker

Figure 4: Shows Galvanic corrosion between steel and concrete

Figure 5: Shows Fungi-induced MIC in a steel pipe

Figure 6: Shows SCC in a steel pipeline-joint

Figure 7: The Mixed methods approach

Figure 8: Petrol (in the front) and Diesel (in the back) Strategic Fuel Reserves

Figure 9: NOCMA diesel and petrol pipelines

Figure 10: Tanker trucks used to transport petrol and diesel

Figure 11 a): Cathodic Corrosion Protection schematic

Figure 11 a): Pipeline under Cathodic protection

Figure 12 a): An Ultrasonic Corrosion Detector

Figure 12 b): Schematic showing how an ultrasonic corrosion detector works

LIST OF TABLES

Table 1: distribution of SFR volumes in Malawi

Table 2: Interview results at both NOCMA and Total

Table 3: Observations at NOCMA and Total

Table 4: Number of corrosion-related accidents in the industry from 2020-2022

CHAPTER 1: INTRODUCTION

Background

The petroleum industry is a vital component of modern economies, providing energy and fuel for transportation, heating, and manufacturing. It encompasses a range of activities, including the exploration and production of hydrocarbons (crude oil and natural gas), the transportation of these resources through pipelines or shipping, their refinement in oil refineries, and their subsequent distribution and commercialization to various markets ("Oil Gas Ind. Energy Transitions," 2020). It is typically divided based on the three segments of the oil and gas value chain: the up-stream, mid-stream and down-stream segments. The up-stream sector involves the exploration and production of Crude oil and Natural gas, the mid-stream sector involves the transportation and storage of the produced crude oil and natural gas before refining and, lastly, the down-stream sector involves refining the crude oil and natural gas into end-products and their transport, storage and distribution (McClay, 2022).

Malawi is a landlocked country located in southeastern Africa and it does not produce oil and gas domestically despite Lake Malawi being confirmed to contain oil deposits (Mwenemungwe, 2012) making it part of the down-stream segment of the petroleum industry. In the country, the downstream segment of the petroleum industry is still in its early stages of development, with limited infrastructure and relatively low demand. However, it is expected to grow significantly in the coming years, as the country's economy expands and urbanization increases. As such, it is critical to ensure that the infrastructure supporting the downstream petroleum industry is safe, reliable, and efficient.

Corrosion can be defined as a chemical or electrochemical reaction between a material, usually a metal, and its environment that leads to the deterioration of the material and its properties (Fontana, 1987). Corrosion has significant negative effects in the downstream petroleum industry that only consists of importing refined petroleum products such as how it can affect the safety, reliability and efficiency of pipelines, storage tanks and distribution systems that transport refined petroleum products. It can lead to leaks, ruptures, fires, explosions and environmental contamination resulting in economic losses, operational

disruptions and legal liabilities (Al-Moubaraki & Obot, 2021). In Malawi, products like petrol and diesel, are often transported and stored in metal containers, such as tanks, which are susceptible to corrosion. These attacks on the storage and transportation material often lead to leakages of the product such as the case that occurred in Limbe where leaking diesel was mistaken for naturally occurring crude oil (Kayaye, 2020). Local residents and business owners in the area stipulate that a corroded storage tank led to the spillage of the product. With this, the research aims to investigate further on corrosion in the country's petroleum industry and find ways to improve on the current corrosion prevention and control techniques.

Problem Statement

As the downstream segment of the petroleum industry in Malawi is estimated to grow in the coming years, there is a risk that corrosion damage to infrastructure could pose significant economic and safety implications. However, there is currently a lack of research on the causes and extent of corrosion damage in Malawi's downstream petroleum industry, as well as effective strategies to prevent and mitigate corrosion. Therefore, this research proposal aims to investigate the effects of corrosion in Malawi's downstream petroleum industry, with a focus on identifying the causes of corrosion, evaluating the extent of corrosion damage, and developing strategies to prevent and mitigate corrosion.

Main and Specific Objectives

The main objective of this research is to investigate and study the effects of corrosion in Malawi's petroleum industry with the goal of improving the performance and reliability of equipment and infrastructure.

Specifically, the research aims to:

a. To understand the specific causes of corrosion in Malawi's downstream petroleum industry.
b. To investigate the mechanisms of corrosion acting on storage and transportation tanks in Malawi.
c. To find out the effects of corrosion in the industry and the mitigation techniques applied.

Research Questions

This research aims to answer the following questions for the purpose of the study:

a. What are the primary causes and mechanisms of corrosion in the storage and transportation tanks of Malawi's downstream petroleum industry?
b. What are the underlying mechanisms of corrosion that affect the integrity of storage and transportation tanks in Malawi?
c. What are the environmental, economic and health impacts of corrosion in Malawi's downstream petroleum industry and how can they be improved on?

Significance of the Study

Investigating the effects of corrosion in the petroleum industry has several significant implications. Firstly, corrosion can lead to significant losses of revenue for the industry due to equipment failure and replacement costs. For instance, in the United States, it is estimated that corrosion alone costs their oil and gas industry about $170 billion per annum (Brondel, et al.). As mentioned above, the petroleum industry of Malawi, though downstream, is estimated to grow in the coming years. With this impending development, risks (such as loss of product and revenue) in the industry are elevated as well. Therefore, identifying the factors that contribute to corrosion and improving on the current mitigation strategies can lead to management and even evasion of such risks. Secondly, corrosion can have serious negative effects on the environment due to spills and leaks of product during either transportation or storage. These incidents can have negative impacts on the health of the local residents as well as the ecosystem making the objectives of this research a significant way of preventing corrosion and result in positive environmental implications. The findings of this study can also be used to inform future research and policy decisions in the field.

CHAPTER 2: LITERATURE REVIEW

Corrosion, the deterioration of a metal or its properties, attacks every component at every stage of the oil and gas field. From the drilling site to the refineries and distribution, corrosion is an adversary worthy of all the high technology and research that can be carried out (Brondel, et al.). Although Malawi's petroleum industry is small and only involves the importation and distribution of refined petroleum products, it is not exempt from the harsh effects of corrosion. The causes of corrosion upstream, midstream and downstream may differ, to some extent, due to the difference in the material being used and the environment dominating that sector of the petroleum industry. For instance, hydrogen sulphide (H_2S), a naturally occurring gas generated by sulphate-reducing bacteria called **Desulfovibrio Desulfuricans** that can found be during oil exploration, is a highly corrosive agent commonly found only during oil exploration (Garverick, 1994). Just like there are various causes of corrosion in each sector, there also exist various methods of controlling and techniques to monitor it in each sector.

Materials for constructing the infrastructures for storage and transporting petroleum products

After refining, petroleum products are stored and transported in tankers, pipelines, railway, tank cars or tank trucks. These are typically constructed using various materials depending on the specific requirements such as the type of stored product, operating conditions and regulations. Steel is the most commonly used materials for constructing the infrastructures for storing and transporting petroleum products. It is a common material for building tanks, pipelines, tank cars and tank trunks due to its high strength, durability and its ability to withstand high pressures and temperatures. It endures high stresses without cracking and is the high-performance choice for underground tanks (The Strength of Steel, 2012). However, it may be affected by some corrosive agents in petroleum products, such as water, oxygen, sulfur compounds, bacteria and acids. It is for this reason, steel needs to be protected by coatings, cathodic protection or corrosion inhibitors. Several types of Steel metals are used in the different sectors of the petroleum industry. Currently, in the downstream sector, the most widely used steel alloy for the construction of storage and

transport infrastructures such as pipelines and tanks is **Carbon steel**. This is a type of steel that contains carbon as the main alloying element (0.05 up to 2.1 percent in weight). Carbon steel is one of the most common materials used for constructing the infrastructures responsible for storage and transporting petroleum products, such as tanks, pipelines, pumps, and valves. Carbon steel has advantages such as high strength, good ductility, and excellent machinability. However, carbon steel is also susceptible to rust and corrosion, especially in environments with high moisture levels and/or salt (Tan, A, & A, 2015). There are various types of carbon steel being employed as materials for Strategic Fuel Reserves as well as pipelines based on the carbon content and the properties they have. These are:

a. **Low-carbon steel (mild steel):** This type of carbon steel contains less than 0.3% carbon by weight. It has low strength but high ductility and weldability. It is used for making pipes, fittings, and other components for the oil and gas industry.
b. **Medium-carbon steel:** This type of carbon steel contains between 0.3% and 0.6% carbon by weight. It has higher strength than low-carbon steel but lower ductility and weldability. It is used for making gears, shafts, and axles for the oil and gas industry.
c. **High-carbon steel:** This type of carbon steel contains between 0.6% and 1% carbon by weight. It has very high strength but low ductility and weldability. It is used for making cutting tools, such as chisels and high-strength wires.
d. **Ultra-high-carbon steel:** This type of carbon steel contains more than 1% carbon by weight. It has extremely high strength but very low ductility and weldability. It is used for making special-purpose tools, such as knives and blades.

Causes of corrosion in the downstream sector of the petroleum industry

Corrosion in refined petroleum product storage and transportation can be caused by a number of factors.

a. **Moisture ingress** can occur through various sources including atmospheric humidity, condensation, rainwater infiltration or leakage from seals and vents. When moisture contacts the tank's interior surfaces, it creates an electrolyte environment necessary for corrosion to occur (Combat In-Tank Corrosion, 2023). Corrosion reactions in the presence of moisture typically involve the transfer of electrons (oxidation and

reduction reactions) and can be influenced by factors such as pH, temperature, and the presence of dissolved ions (Roberge, Corrosion Engineering: Principles and Practice, 2008).

b. Refined petroleum products may contain corrosive compounds such **as sulfur compounds** (e.g., hydrogen sulfide), **organic acids**, or **chlorides** (Papavinasam, 2013). Sulfur compounds, especially in the presence of moisture, can lead to the formation of sulfuric acid, which is highly corrosive to metals. It causes uniform corrosion, pitting corrosion, crevice corrosion, stress corrosion and intergranular corrosion of metals and alloys (Roberge, Forms of Corrosion, 2008). Organic acids, such as naphthenic acids, can also cause corrosion, particularly in the presence of moisture and oxygen. Chlorides, commonly found in seawater or certain petroleum products, can accelerate corrosion processes, especially in the presence of moisture.
c. Microbial corrosion, or microbiologically influenced corrosion (MIC), occurs when microorganisms thrive in the presence of water and organic compounds found in petroleum products. **Microbes** produce byproducts, such as organic acids or sulfides, as part of their metabolic processes, which can contribute to corrosion. Microbial corrosion can be particularly problematic in the presence of biofilms, which are communities of microorganisms that adhere to the tank's surfaces and provide a protective environment for corrosion-causing organisms.
d. **Oxygen** is a key factor in many corrosion reactions and can initiate oxidation reactions. In the presence of moisture, oxygen can react with metal surfaces, leading to the formation of metal oxides and corrosion products.
e. **Particulate matter** or **sediments** present in petroleum products can act as abrasives, causing mechanical wear on protective coatings or tank surfaces. Abrasion and erosion can weaken or remove protective layers, exposing the underlying metal to corrosion.
f. Protective coatings or linings are applied to tank surfaces to create a barrier between the metal and corrosive substances. **Damaged** or **deteriorating coatings** can allow corrosive agents to directly interact with the metal surface, leading to corrosion.

Coating failures can occur due to inadequate application, improper curing, mechanical damage, or chemical degradation over time.

Types of Corrosion/ Corrosion mechanisms

In the petroleum product distribution sector of the downstream petroleum industry, several types of corrosion can occur.

a. **Uniform Corrosion** is the most common type of corrosion, where the metal surface corrodes uniformly over the entire area (Uniform Corrosion, n.d.) as illustrated by *figure 1* below.



Figure 1: Uniform corrosion in carbon steel

It can render large amounts of material useless quite rapidly because the attack occurs across the entirety of the exposed surface (Uniform Corrosion, 2019). Uniform corrosion can occur in the petroleum product distribution sector when the metallic constructions and equipment such as storage and transportation tanks are exposed to corrosive agents such as water, oxygen, sulfur compounds, bacteria and acids (Groysman, Corrosion of Metallic Constructions and Equipment in Petroleum Products, 2014). These agents may be present in the products themselves (perhaps after the refinery process) or in the environment they are being stored in.

b. **Pitting Corrosion** is a localized form of corrosion by which cavities or "holes" are produced in the material. It is considered to be more dangerous than uniform corrosion because it is more difficult to detect since the corrosion products often cover the pits, making them hard to see (Pitting Corrosion, n.d.).



Figure 2: Pitting corrosion in Carbon steel

Pitting corrosion can happen in the distribution sector when the metal infrastructures are exposed to aggressive agents such as chlorides, sulfides, nitrates or organic acids (Harrop & Kermani M, 1996).

c. **Crevice Corrosion** occurs in confined spaces or crevices, such as gaps between metal surfaces or under gaskets or deposits. It can be very damaging because it is hard to detect and can cause rapid metal loss (Asmatulu, Alavi-Soltani, & Rashidi, 2007). The corrosive agents responsible for this mechanism of corrosion such as water, oxygen, sulfur compounds, bacteria and acids (Groysman, Corossion of Metallic Constructions and Equipment in Petroleum Products, 2014). ***Figure 3*** demonstrates an instance of a steel drum undergoing crevice corrosion.



Figure 3: Crevice corrosion in a steel tanker

d. **Galvanic Corrosion** is a type of corrosion that occurs when two dissimilar metals come into electrical contact in the presence of an electrolyte, such as moisture, oil or soil. The more reactive metal (anode) undergoes accelerated corrosion, while the less reactive metal (cathode) corrodes slowly (Tuttle, Corrosion in Oil and Gas Production, 1987).



Figure 4: Galvanic corrosion between steel and concrete

e. **Microbial Corrosion (Microbiologically Influenced Corrosion - MIC)** is influenced by the metabolic activities of microorganisms, such as bacteria, archaea, algae or fungi (see figure 4 below), in the presence of moisture and specific environmental conditions (Maruthamuthu, et al., 2011). The microorganisms may produce

corrosive byproducts, consume or produce electrons, form biofilms, or alter the physicochemical properties of the environment thereby accelerating the corrosion process (Procopio, 2022). MIC can happen in the petroleum distribution sector when microorganisms grow and thrive in the petroleum products or in the water that is associated with them. Microorganisms can be introduced into the petroleum products from various sources such as soil, water, air or additives. Some of the most common microorganisms involved in microbial corrosion are sulfate-reducing bacteria (SRB), acid-producing bacteria (APB), iron-oxidizing bacteria (IOB), iron-reducing bacteria (IRB) and methanogenic bacteria (MA) (Rajasekar, Anandkumar, Maruthamuthu, Ting, & Rahman, 2009).



Figure 5: Fungi-induced MIC in steel

f. **Stress Corrosion Cracking (SCC)** is the cracking of a metal under the combined influence of tensile stress and a corrosive environment. It can occur in susceptible materials when exposed to specific corrosive agents, leading to brittle fracture. Figure 6, below illustrates an example of a portion of a carbon steel pipeline that underwent Stress Corrosion Cracking.



Figure 6: SCC in a pipeline

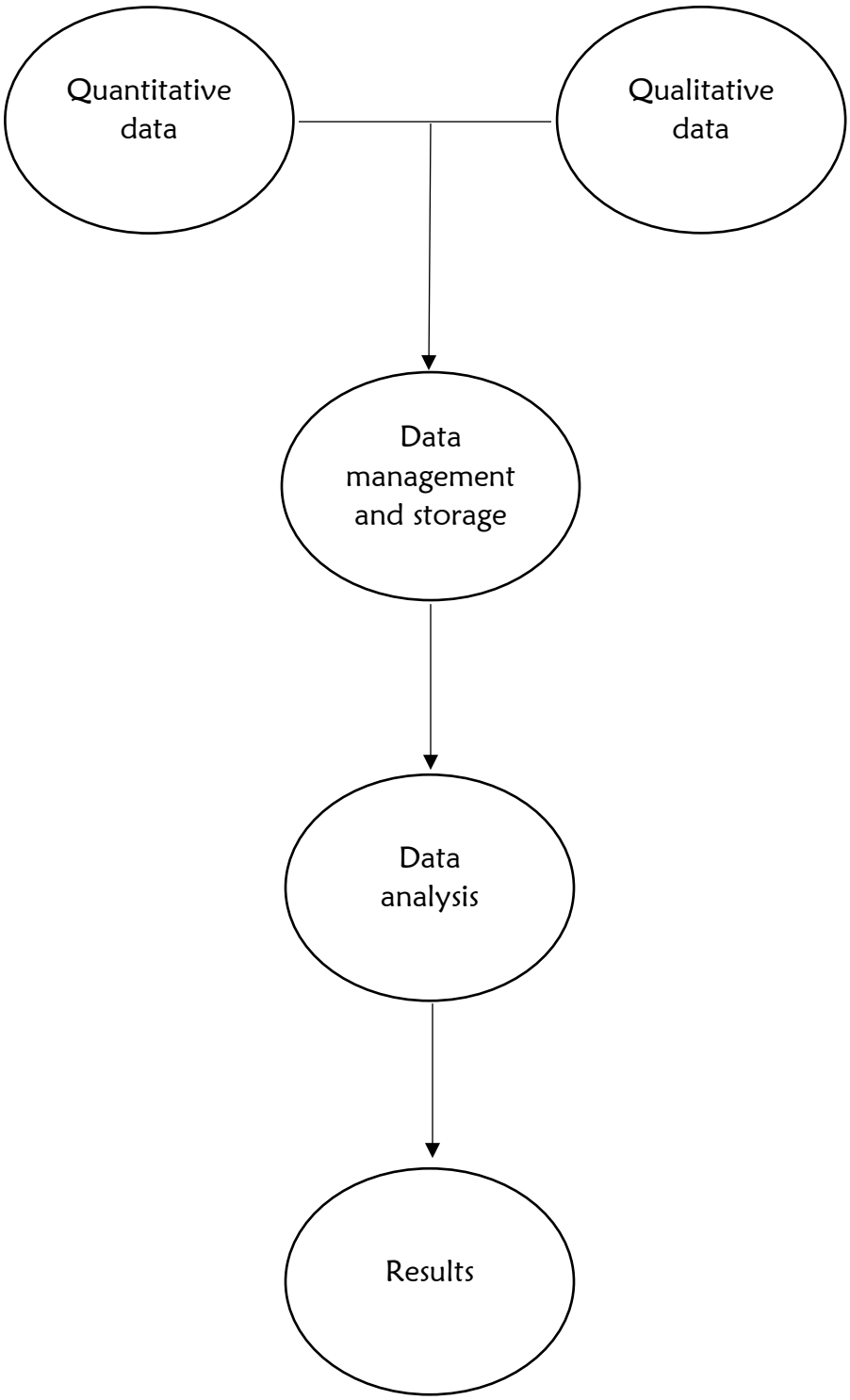
SCC can cause cracks to form and propagate in the metal, leading to failure or reduced performance of the equipment. Some of the factors that influence SCC are the type of metal, the type of corrosive agent, the temperature, the pressure, and the presence of cracks or defects in the metal. Some metals are more susceptible to SCC than others, depending on their composition and microstructure. For example, carbon steel and stainless steel are prone to SCC when exposed to hydrogen sulfide (H_2S) or chloride ions (Cl^-), which are common in refined petroleum products (Tuttle, Corrosion in Oil and Gas Production, 1987). The corrosive nature of the oil, combined with the tensile stresses exerted on the tank walls can lead to SCC which may result in tank failure, leaks and environmental damage, among other negative effects (Stress Corrosion Cracking: Overview & How to Reduce Risks, 2023). Some corrosive agents can cause specific types of SCC, such as hydrogen-induced cracking (HIC), sulfide stress cracking (SSC), or chloride stress corrosion cracking (CSCC). The temperature and pressure can affect the rate and degree of SCC, as they can influence the chemical reactions and the stress levels in these metal. The presence of cracks or defects in the metal can act as initiation sites for SCC, as they can concentrate the stress and the corrosive agent in the metal.

These types of corrosion can affect storage tanks, pipelines, valves, fittings, and other infrastructure components in the petroleum product distribution sector. Understanding these corrosion mechanisms is crucial for implementing effective corrosion control measures and selecting appropriate materials to mitigate the risk of corrosion.

CHAPTER 3: METHODOLOGY

Research Design

Figure 7: The Mixed methods approach



Data collection

This research adopted a *mixed-methods approach*, combining quantitative and qualitative methods of data collection which allowed a comprehensive and more in-depth understanding of the topic by combining the strengths of both quantitative and qualitative research.

The quantitative methods involved collecting numerical data including the number of corrosion-related incidents, their causes, and the effectiveness of mitigation techniques.

The qualitative methods, on the other hand, consisted of collecting non-numerical data including interviews with industry experts and maintenance personnel (at NOCMA in Matindi and Total filling station in Blantyre market) and observations of on-site truck tankers, pipelines and Strategic Fuel Reserves (SFRs) at NOCMA. These methods provided rich and contextual insights into people's experiences, perspectives, and beliefs to shed some light on corrosion mechanisms on storage and transportation tanks in Malawi, their impacts, and suggestions for improvement.

By combining quantitative and qualitative methods, comprehensive understanding of the research topic was obtained. The quantitative data provided statistical evidence and numerical trends, while the qualitative data offered deeper insights, contextual information, and diverse perspectives on the topic. The integration of both approaches helped enhance the validity and reliability of the research findings.

Ethical considerations such as obtaining clearance, ensuring informed consent from company personnel in NOCMA and Total and protecting participant confidentiality were followed.

Informed consent is a fundamental ethical principle that ensures participants are fully aware of the research purpose, procedures, risks, benefits, and their rights before agreeing to participate. Participants were provided with a clear and detailed explanation of the research, allowing them to make an informed decision about their participation. Consent was voluntary and obtained through written consent forms (reference letters provided by the school) as well as verbal consent.

Data Storage and management

Data management is a critical aspect of any research, particularly when it comes to handling and storing research data securely.

Data was stored in a secure password-protected computer and backed-up on external hard-drives. The backup copies of the data were mitigate any loss or accidental deletion.

Materials and Methods used in the research

For data collection in this research, various materials were involved. These were the Strategic Fuel Reserves and pipelines at NOCMA and the truck-tankers at Total.

Strategic Fuel Reserves are facilities that contain large quantities of crude oil stored by governments or private companies to ensure the security and stability of energy supply in case of disruption or crisis (Global strategic petroleum reserves, 2021). SFRs in Malawi are constructed using low-carbon steel due to its low cost and weldability. NOCMA is a government owned company that was formed in line with the National Energy Policy of January 2003. It is mandated to manage the country's SFR facilities among other responsibilities. The company has three national deposits which sum up a volume of 60 million liters shown in **figure 8** below.

Table 1: distribution of SFR volumes in Malawi

Location of SFR	Petrol volume (in liters)	Diesel volume (in liters)	**Total (in liters)**
Blantyre	7,000,000	18,000,000	25,000,000
Lilongwe	7,000,000	18,000,000	25,000,000
Mzuzu	5,000,000	5,000,000	10,000,000
Total (in liters)	19,000,000	41,000,000	60,000,000

The conditions of these facilities was observed to determine the degree and type of corrosion that dominates the environment they are in.

Petrol and diesel are off-loaded at NOCMA from truck tankers and railway wagons. Before unloading, the trucks undergo a system of pre-entry checks where measurements and tests

are done on the products to ensure that they are up to designated standards. The measurements include recording the logistics, the weight as well as the volume among others. From railway, the company has pipes that guides the petrol and diesel in separate lines to the pump house as shown in **figure 9** below. These pipelines are constructed from medium-carbon steel due to its relatively lower cost compared to high-carbon steel, ductility and weldability. These were also observed for the purpose of determining their condition and the mechanism of corrosion acting on them, if any.

Tank-trucks or tanker trucks (as shown in **figure 10**) are vehicles designed to transport liquid and gas cargo, such as petrol and diesel, in large cylindrical tanks and is one of the main mode of transporting these products in Malawi. These tanks were observed at Total to determine the mechanism of corrosion that acts on them as well as their condition.

Due to safety regulations at both NOCMA and Total, it was discouraged to acquire photos of the Strategic Fuel Reserves, pipelines as well as tank-trucks as coming close to such volatile product facilities with a mobile device could pose the risk of a fire. For the purpose of understanding the above described infrastructures and equipment, below are photographs of the SFR and tanker trucks retrieved from the NOCMA webpage.



Figure 8: Petrol (in the front) and Diesel (in the back) Strategic Fuel Reserves



Figure 9: NOCMA diesel and petrol pipelines



Figure 10: Tanker trucks used to transport petrol and diesel

CHAPTER 4: RESULTS AND DISCUSSION

1. Qualitative data

a. Interview results

Table 2: Interview results at both NOCMA and Total

Interview question	NOCMA reply	Total reply
What type of metal (or steel) is used for the construction on the SFRs and pipelines?	"The current metal being used as the material for constructing the SFRs is low-carbon steel while the pipelines are made of medium-carbon steel."	"The company's tanker trucks are constructed from medium-content carbon because of the higher durability compared to lower carbon content steels."
Have there been any encounters with corrosion in the industry?	"Due to the nature of the product that is stored here, there have been a few cases were we've had leakages due to corroded pipelines."	"Yes. There have been leakage cases on the premise as well as during transport on the road due to cracks forming on the walls of the tankers from corrosion."
What may have been the causes of these incidents?	"Mostly moisture coming in contact with the metal structures."	"The exposure of the tanker trucks to the weather elements during transportation such as the changes between rain and sunshine."

What were the effects of the corrosion incidents that occurred over the years in this storage and distribution facility?	"Corrosion in this industry has led to delays due to equipment failure and high costs to maintain them."	"The costs for maintaining these ruined infrastructures is pretty high especially in the rare cases that they need to be replaced."
What were the monitoring, elimination or mitigation measures you employed to combat the above-mentioned negative effects of corrosion in the facility?	"As of currently, there haven't been any advancements in the monitoring of corrosion so the responsibility of observing and determining the integrity of the infrastructures is trusted to experienced personnel such as the maintenance crew. As for the prevention, painting the metallic components is what is done to reduce the contact between them and the corrosive components."	"Paint is coated on the tankers eliminate the contact between it and the corrosive environment. Direct observation is the only used method of detecting and monitoring corrosion."
Are the employed techniques of a satisfactory nature in the industry or would you say there is a way to improve on them?	"As one might guess, painting is not so effective when trying to prevent corrosion since it may peel off after a while leaving the metal	"Paint peels off after the use of the tankers and their exposure to the interchange between rainfall and sunshine. This leaves the metal exposed

	unprotected. And also human error is a huge disadvantage in direct observation which leads to misjudgment of the integrity of the infrastructures."	to the elements all over again.

b. Observation results

Table 3: Observations at NOCMA and Total

Material	Observation
Strategic Fuel Reserves (SFRs)	Minor corrosion and cracks at the bottom plates Some corrosion between the plates of the SFR
Pipelines	Corrosion across the surface of some of the sections in the line
Tanker trucks	Corrosion across the outer surface of the tanker

2. Quantitative data

Table 4: Number of corrosion-related accidents in the industry from 2020-2022

Year	Effect	NOCMA	Total Energies
	Leaks	1	5

2020	Equipment failure	2	3
	Fires	0	0
2021	Leaks	2	3
	Equipment failure	1	3
	Fires	0	0
2022	Leaks	1	3
	Equipment failure	0	2
	Fires	0	0

As mentioned in the literature review, uniform corrosion is the type of corrosion where the metal surface corrodes uniformly over the entire area. From the observation conducted on the pipeline and tankers, it can be seen that the prevailing corrosion mechanism in such infrastructures is uniform corrosion. It may have been caused due to the exposure of the metal surface to water from rainfall or moisture ingress and also the exposure of the metal to oxygen.

The cracks and minor corrosion at the bottom plates of the Strategic Fuel Reserve were due to the high tensile forces acting on them from all the overlying plates as well as their exposure to the corrosive weather environment. Based on the information provided by two experts at NOCMA, it is known that the SFRs are constructed using low-carbon content steel alloy. This is because this type of steel alloy is of a lower cost and higher ductility as well as weldability than the other types of carbon-steel alloys. The downside of using this type of steel alloy is that it has low resistance to high tensile force situations. This means, unlike high-carbon steel, low-content steel is much more likely to form cracks or fractures if put in scenarios where it has to support high overlying weight. The cracks were due to tremendous weight of the overlying steel plates and the corrosion was due to

the environment the SFRs were placed. This means in this environment, the dominating mechanism of corrosion is SCC (Stress Cracking Corrosion).

As expected, such attacks on these infrastructures have had significant effects on the industry operations and revenue. According to the experts from NOCMA and Total, corrosion has led to a number of incidences that proved to be disadvantageous to the industry such as the leakages as well as well the equipment failure. The cost of controlling the repercussions caused by these attacks as well as maintaining and replacing the structures and vehicles is substantial and incurs negative effects of the revenue.

The mitigation measure of painting the metal surface to create a barrier and prevent contact with the corrosive elements is the most frequently used in various industries in Malawi but, as explained from interviews, it is not as effective due to its short lifespan.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

CONCLUSION

This research has determined that the main corrosion mechanisms in Malawi's downstream petroleum sector are Uniform and Stress Cracking Corrosion (SCC) based on the observation of the SFRs and pipelines at NOCMA, and the tanker trucks at Total. From the study, the following conclusions were made:

a. The main causes of corrosion in the industry are the exposure of the metal structures to rainfall.
b. Corrosion leads to high expenditures in the industry in attempts to mitigate its effects
c. The current prevention measures are not effective enough to combat corrosion

RECOMMENDATIONS

With the effectiveness of the mitigation measures being so low, the following practices could be employed to better fight against corrosion. These are:

a. Employing cathodic protection:

   This is a technique that prevents the metal surface from corroding by making it the cathode of an electrochemical cell. This means the metal is protected from losing electrons and becoming oxidized, which is the main concept behind corrosion (Nanan, 2020). Figure 11 a) and b) below illustrate an instance of a metal surface under cathodic protection.

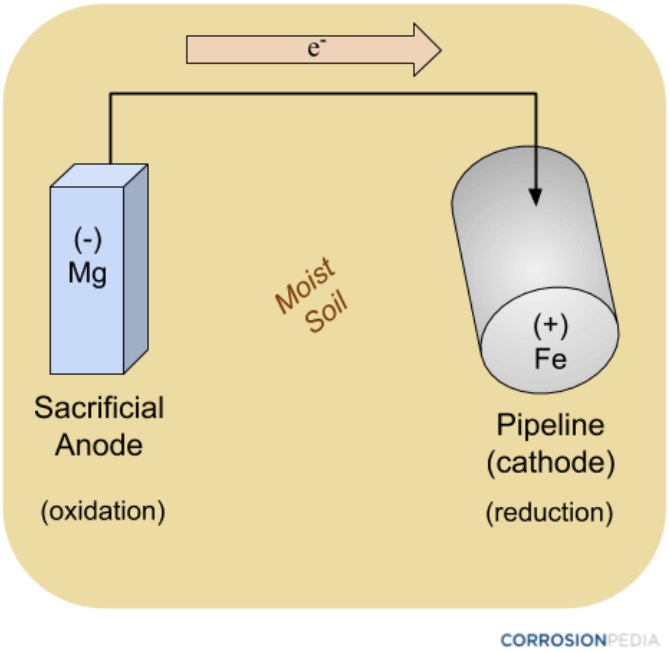


Figure 11 a): Cathodic Corrosion Protection schematic



Figure 11 a): Pipeline under Cathodic protection

Compared to painting the metal surfaces of the SFRs, tanks and pipelines, this method of controlling and preventing corrosion extends the service life and performance of metal structures, reduces maintenance costs and risks and also protects the environment and the safety of employees.

b. Employing the use of ultra-sonic corrosion detection:

This technique of corrosion detection eliminates the effects of corrosion in the industry by removing the component of human error. It uses high frequency sound waves to measure the thickness and condition of metal surfaces such as pipelines, tanks, vessels and structures. It can detect the extent and presence of corrosion at a level which the human eye cannot observe. As an added advantage, ultra-sonic corrosion detection is a type of non-destructive testing (NDT) which means that it does not change or damage the material which it is being used on (Ultrasonic Corrosion Monitoring, 2018).



Figure 12 a): An Ultrasonic Corrosion Detector

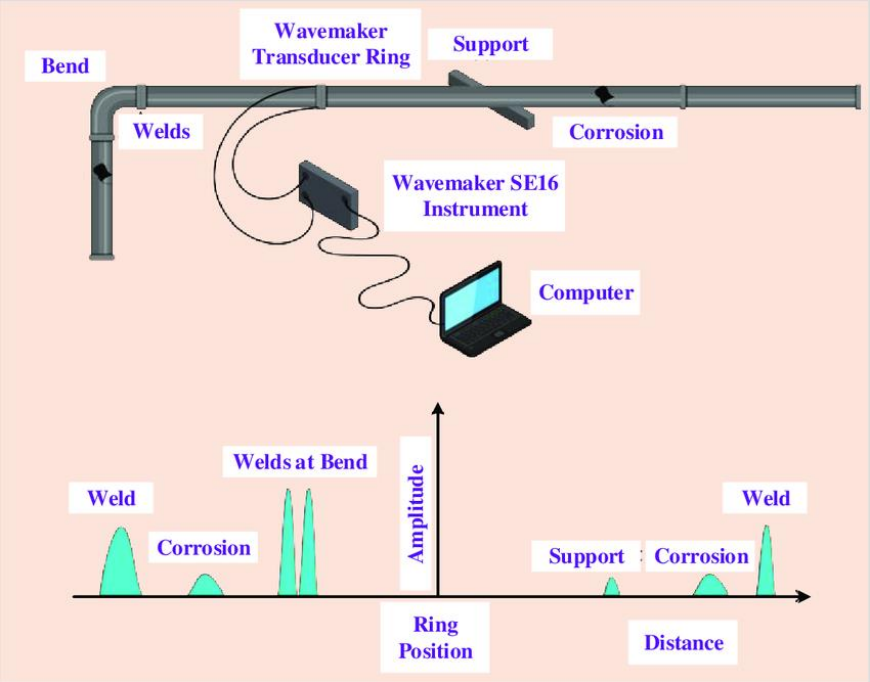


Figure 12 b): Schematic showing how an ultrasonic corrosion detector works

Ultra-sonic detection is highly accurate, faster, more sensitive and portable. It can measure the thickness and condition without requiring any direct contactor access to both sides. It can also detect all kinds and mechanisms of corrosion from Uniform to MIC compared to direct observation which may show difficulty in detecting Pitting corrosion (Schleke & Geisenhoff, 2021).

References

Al-Moubaraki, A. H., & Obot, I. B. (2021). Corrosion Challenges in Petroleum Refinery Operations: Sources, Mechanisms, Mitigation and Future Outlook. *Journal of Saudi Chemical Society*.

Asmatulu, R., Alavi-Soltani, S., & Rashidi, N. (2007). Crevice Corrosion Theory, Mechanisms and Prevention Methods. *Graduate Research and Scholarly Projects* (p. 1). Kansas: Wichita State University.

Brondel, D., Edwards, R., Hayman, A., Hill, D., Mehta, S., & Mobil, T. S. (n.d.).

Combat In-Tank Corrosion. (2023, June 21). Retrieved from VEEDER-ROOT: https://www.veeder.com/us/combat-corrosion/combat-tank-corrosion

Fontana, M. G. (1987). Corrosion Damage. In M. G. Fontana, *CORROSION ENGINEERING* (pp. 5-6). Singapore: McGraw-Hill Book Company.

Garverick, L. (1994). *Corrosion in the petrochemical industry.* Ohio: ASM International.

Global strategic petroleum reserves. (2021, July). Retrieved from WIKIPEDIA: https://en.m.wikipedia.org/wiki/Global_strategic_petroleum_reserves

Groysman, A. (2014). Corossion of Metallic Constructions and Equipment in Petroleum Products. In A. Groysman, *Corrosion in Systems for Storage and Transportation of Petroleum Products and Biofuels* (pp. 57-143). New York: Springer Science & Business Media.

Groysman, A. (2014). Corrosion of Metallic Constructions and Equipment in Petroleum Products. In A. Groysman, *Corrosion in Systems for Storage and Transportation of Petroleu Products and Biofuels* (pp. 57-143). New York: Springer Science & Business Media.

Harrop, D., & Kermani M, B. (1996, August 1). *The Impact of Corrosion on the Oil and Gas Industry.* Retrieved from OnePetro: https://doi.org/10.2118/29784-PA

Kayaye, B. (2020, November 20). Mining & Trade News. *Malawi Online News*. Retrieved from Malawi Online News: https://miningtradenews.net/no-natural-gas-in-limbe-says-malawi-government

Maruthamuthu, S., Kumar, B. D., Ramachandran, S., Anandkumar, B., Palanichamy, S., Chandrasekeran, M., . . . Palaniswamy, N. (2011). Microbial Corrosion in the Petroleum Product Transporting Pipelines. *Industrial & Engineering Chemistry Research*.

McClay, R. (2022, September 24). *How the Oil and Gas Industry Works.* Retrieved from Investopedia: https://www.investopedia.com/investing/oil-gas-industry-overview/

Mwenemungwe, R. (2012). Oil Exploration, Mining Threaten Lake Malawi. *EARTH ISLAND JOURNAL*.

Nanan, K. (2020, June 29). *The Basics of Cathodic Protection*. Retrieved from CORROSIONPEDIA: https://www.corrosionpedia.com/2/1368/prevention/cathodic-protection/cathodic-protection-101

Papavinasam, S. (2013). *Corrosion Control in the Oil and Gas Industry.* Ohio: Gulf Professional Publishing.

Pitting Corrosion. (n.d.). Retrieved from AMPP: https://www.ampp.org/technical-research/impact/corrosion-basics/group-1/pitting-corrosion

Procopio, L. (2022). Microbially induced corrosion impacts on the oil industry. *Archives of Microbiology*.

Rajasekar, A., Anandkumar, B., Maruthamuthu, S., Ting, Y.-P., & Rahman, P. K. (2009). Characterization of corrosive bacterial consortia isolated from petroleum-product-transporting pipelines. *Environmental Biotechnology*.

Roberge, P. R. (2008). *Corrosion Engineering: Principles and Practice.* Ohio: McGraw-Hill.

Roberge, P. R. (2008). Forms of Corrosion. In P. R. Roberge, *Corrosion Engineering: Principles and Practice* (p. 83). Ohio: McGraw Hill.

Schleke, S., & Geisenhoff, M. (2021, February 15). *Ultrasonic Corrosion Monitoring - It's Time for a Paradigm Shift*. Retrieved from Inspectioneering: https://inspectioneering.com/blog/2021-02-15/9512/ultrasonic-corrosion-monitoring-its-time-for-a-paradigm-shift

Stress Corrosion Cracking: Overview & How to Reduce Risks. (2023, August 26). Retrieved from PETROSYNC: https://www.petrosync.com/blog/stress-corrosion-cracking/

Tan, M. J., A, H. M., & A, S. J. (2015). Materials for the Oil and Gas Industry. In M. J. Tan, H. M. A, & S. J. A, *Materials for Energy Efficiency and Thermal Comfort in Buldings* (p. 140). CRC Press.

The Strength of Steel. (2012, February). *STEEL FACTS*. American Iron and Steel Institute (AISI).

Tuttle, R. N. (1987, July 1). *Corrosion in Oil and Gas Production.* Retrieved from OnePetro: https://onepetro.org/jpt/article-abstract/39/07/756/75133/Corrosion-in-Oil-and-Gas-Production?redirectedFrom=fulltext

Tuttle, R. N. (1987). Corrosion in Oil and Gas Production. *Journal of Petroleum Technology*, 756-762.

Ultrasonic Corrosion Monitoring. (2018, October 17). Retrieved from CORROSIONPEDIA: https://www.corrosionpedia.com/definition/6413/ultrasonic-corrosion-monitoring

Uniform Corrosion. (n.d.). Retrieved from AMPP: https://ampp.org/technical-research/impact/corrosion-basics/group-1/uniform-corrosion

Uniform Corrosion. (2019, September 12). Retrieved from CORROSIONPEDIA: https://www.corrosionpedia.com/definition/6542/uniform-corrosion