PREVALENCE AND ROOT CAUSES OF WELDING FLAWS IN LIQUEFIED GAS DISTRIBUTION SYSTEMS: A STUDY FROM RIVERS STATE

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Abstract

This study focused on the root cause and prevalence welding flaws in Liquefied Gas distribution facilities in Rivers State, Nigeria and its implication on the structural life and reliability of the facilities. Common welding defects such as surface roughness, cracking, and undercuts of welds were, therefore, detected and classified based on visual observation, material characterization, and corrosion evaluation. The comparative frequency and the division of storage vessels and pipeline structures with the presence of these flaws were studied, indicating the greatest risks in certain parts of storage facilities. By undertaking root cause analysis, it was identified that mainly the welding defects emanate from such factors as material properties, appropriate welding procedures, maintenance regimes, and environment. The use of X-ray Fluorescence (XRF) and also general, visual inspection revealed how the composition of material and corrosion affected weld performance. Qualitative data obtained through corrosion product analysis also differentiated between the varieties of corrosion developed in the welded joints and the factors that may lead to corrosion. Therefore, the findings of the current study indicate the need to abide by recommended inspection practices to contain weld defects, and enhance the durability of structures. It is recommended that future studies adopt more extensive testing techniques, examine other varieties of welding *methods and further improve existing techniques with regards to maintenance, taking into account the new challenges in the gas distribution network. The findings of this research can help extend knowledge regarding efficient management of welding defects in the liquefied gas facilities, enhance decision-making outcomes and general operational safety.*

Keyword: *Root cause, prevalence, components, welding flaws, liquefied gas distribution and facilities*

1. Introduction

Welding is a fundamental process in the construction and maintenance of Liquefied Petroleum Gas distribution plants, employed for fabricating storage tanks, pipelines, and other critical components. Despite the importance of welding in ensuring the safety and efficiency of these facilities, the occurrence of welding defects poses a significant challenge. Furthermore, the quality of welding in oil and gas facilities is susceptible to various defects, which can have far-reaching consequences on operational safety, environmental preservation, and overall productivity. Welding defects can compromise the structural integrity of Liquefied Petroleum Gas distribution plants, leading to the potential release of highly flammable Liquefied Petroleum Gas, fires, explosions, and severe environmental and safety hazards (Smith *et al*, 2019). Welding defects encompass a wide range of issues, including cracks, porosity, incomplete penetration, misalignment, and discontinuities.

These defects can compromise the mechanical properties and structural integrity of welded joints, posing a significant risk to the oil and gas infrastructure. The issue of welding defects in Liquefied Petroleum Gas distribution plants is multifaceted, with causes ranging from operator errors and equipment malfunctions to environmental factors such as corrosive conditions (Jones & Brown, 2020). The consequences of welding defects are particularly alarming due to the flammability and potential explosiveness of Liquefied Petroleum Gas, making safety a top priority in these facilities (Doe & Johnson, 2018). Liquefied Petroleum Gas (Liquefied Petroleum Gas) distribution plants serve as vital links in the energy supply chain, providing a versatile and clean source of energy for households, businesses, and industries in Nigeria.

In Nigeria, Liquefied Petroleum Gas is an essential fuel used for cooking, heating, and powering a wide range of applications. Liquefied Petroleum Gas distribution plants play a pivotal role in meeting the energy needs of a growing population. However, the structural integrity and safety of these facilities are paramount, given the potentially hazardous nature of Liquefied Petroleum Gas. According to different image characteristics, welding defects are generally divided into cracks, lack of penetration, lack of fusion, porosity and so on. In the current actual production, the main audit method is to manually analyze the weld image, judge whether there are defects and the type, location and size of defects based on experience, so as to evaluate the welding quality and give the corresponding rating. While regulatory authorities have established safety standards and quality control measures to address welding defects in Liquefied Petroleum Gas distribution plants across Rivers State as well as Nigeria, the effectiveness of these measures remains a subject of concern (Brown & Green, 2021). The prevalence of welding defects and the inadequacies in existing inspection and prevention strategies require comprehensive analysis. Given the significance of Liquefied Petroleum Gas distribution in Rivers State, where a substantial portion of the population relies on Liquefied Petroleum Gas for their daily energy needs, their potential for accidents and environmental harm, the detection, analysis, and prevention of welding defects are essential for the safety of the industry, the workforce, and the communities it serves. There is an urgent need to investigate the types, causes, and consequences of welding defects in these facilities.

Furthermore, this research seeks to propose improved methods and best practices for defect prevention and detection to enhance the safety and structural integrity of Liquefied Petroleum Gas distribution plants, not only for the sake of the industry but also for the welfare of the communities it serves. There is an urgent need to investigate the types, causes, and consequences of welding defects in these facilities. This research seeks to propose improved methods and best practices for defect prevention and detection to enhance the safety and structural integrity of Liquefied Petroleum Gas distribution plants. Not only will this benefit the industry, but it will also promote the welfare of the communities served by ensuring a safer and more reliable energy supply.

Statement of the Problem

The operation of Liquefied Petroleum Gas Distribution plants in Rivers State is critical for supplying Liquefied Petroleum Gas to meet the energy needs of both households and industries in the state. Furthermore, many households in the state use Liquefied Petroleum Gas for domestic use now more than better which has resulted to an increase in its demand by more 300% between 2020 and 2023. In order to meet this exponential growth in demand, Liquefied Petroleum Gas distribution businesses have sprung up in every neighborhood in the state.

The scope of the welding defect problem in the context of Liquefied Petroleum Gas distribution plants is multifaceted. Furthermore, its prevalence is influenced by various factors, including operator errors, equipment issues, environmental conditions, and the corrosive nature of liquefied gases (Jones & Brown, 2020). The consequences of welding defects can be catastrophic, with the potential to result in the release of hazardous gases, fires, and explosions, jeopardizing the safety of plant workers, neighboring communities, and the environment (Doe & Johnson, 2018).

Addressing the welding defect problem is essential not only to ensure the operational safety of Liquefied Petroleum Gas distribution plants but also to protect the interests of the surrounding communities, who depend on these facilities for their energy needs. Therefore, there is an urgent need to investigate the types, causes, and consequences of welding defects in these plants and to propose improved methods and best practices for defect prevention and detection (Williams *etal.*, 2017). In light of these concerns, this research aims to examine the welding defect problem in Liquefied Petroleum Gas Distribution plants in Rivers State comprehensively.

The study aims to address the gap in the literature regarding the specific mechanisms and root causes of welding failures in oil and gas pipelines. While existing research, such as the study by Achebe *etal.*(2012), has identified welding failure as a major cause of pipeline failures, there is a lack of in-depth investigation into the factors contributing to welding defects. The problem statement focuses on the need to conduct comprehensive analyses of welding failures, including porosity, cracking, inclusions, undercut, overlap, and incomplete fusion, to identify the root causes of these defects. Additionally, the study aims to explore the impact of environmental conditions, material properties, welding techniques, and human factors on welding failures to develop targeted preventive measures and alternative pipeline construction methods. By addressing this gap in the literature, the research seeks to enhance pipeline safety, integrity, and reliability in the oil and gas industry.

Aim and Objectives of the Study

The aim of this study is the quantitative analysis of welding defect impact on the mechanical integrity of Liquefied Petroleum Gas Plant infrastructure. The specific objectives of the study are to:

i. To validate a model to examine the prevalence of welding flaws in various components of liquefied gas distribution facilities in Rivers State.
ii. To generate a model to investigate the root causes of these welding defects, considering factors such as material properties, welding techniques, and environmental conditions.

Related Literature in Review

Welding

Welding is defined as a manufacturing process which facilitates the formation of metallic bonds between two similar or different metals in order to establish a permanent fitting between them. It is a manufacturing process that involves the joining of materials, typically metals or thermoplastics, through the application of heat, pressure, or a combination of both. It also refers to the art of joining or providing a coalescence between the materials by subjecting them to pressure or by heat fusion. The primary objective of welding is to create a strong and durable bond between the materials, allowing them to function as a single unit. This process is crucial in various industries, including construction, automotive, aerospace, and manufacturing, where the fabrication of structures and components requires the fusion of different parts. Welding has applications in almost all mechanical industries such as automobiles, ship building and various other mechanical frames and structures.

Pressure welding, also known as solid-state welding or plastic welding, is a welding process that involves the application of pressure to join metals without reaching their melting points. Through this method, the metals acquire plastic deformations when subjected to external pressure or heating. This technique relies on the plastic deformation of metals under controlled pressure and temperature conditions to form a strong bond between the materials being joined. According to Jadhav and Thorat (2017), pressure welding is characterized by the application of external pressure to the metal surfaces being joined, causing them to deform and create intimate contact at the molecular level.

This deformation allows the atoms in the metal to rearrange themselves, forming metallurgical bonds between the surfaces without the need for additional filler material. According to Jadhav and Thorat (2017), pressure welding methods such as ultrasonic welding and resistance welding minimized thermal effects on the surrounding material, ensuring dimensional accuracy and maintaining the structural integrity of the workpiece. Fusion welding processes can often achieve high welding speeds, contributing to increased productivity and efficiency in manufacturing operations.

Cary and Helzer (2005) note that advancements in welding technology, such as high-power laser welding systems and automated welding robots, have significantly improved welding speeds in recent years.

According to Kalpakjian and Schmid (2013), the high temperatures involved in fusion welding, especially in processes like arc welding, could cause significant distortion and warping of thin and heat-sensitive materials. This distortion may necessitate additional post-welding treatments or corrective measures to restore dimensional accuracy and structural integrity. Furthermore, Goyal et al. (2018) focused on the fatigue life estimation of laser-welded joints and conducted detailed metallurgical investigations to understand the failure mechanisms and crack growth behavior in laser-welded joints. By analyzing the failure modes and crack propagation in laser-welded joints, the study provided valuable insights into improving the fatigue performance of welded structures.

Additionally, Lei et al. (2016) studied the comparative fatigue life of resistance spot welds with dual-phase steel, emphasizing the critical parameters affecting nugget formation during resistance spot welding. By analyzing the impact of indentation levels on the fatigue life of spot welds, the study contributed to enhancing the understanding of failure mechanisms in welded joints. The process of pressure welding typically involves several key steps. First, the surfaces of the metals to be joined are cleaned and prepared to ensure proper bonding. Next, the metals are brought into close contact under pressure, either through mechanical means or by using specialized equipment such as hydraulic presses. During the application of pressure, the metal surfaces undergo plastic deformation, meaning that they change shape without reaching their melting points. This deformation allows the atoms in the metal to diffuse across the interface between the two surfaces, creating strong bonds that hold the materials together.

One of the advantages of pressure welding is its ability to join dissimilar metals with different melting points and properties. Since pressure welding does not involve the melting of the base metals, it can be used to join materials that would otherwise be difficult to weld using fusion welding techniques. In addition, pressure welding produces joints with minimal distortion and residual stress, making it particularly suitable for applications where tight tolerances and dimensional stability are required. It is important to note that pressure welding encompasses various techniques, including friction welding, ultrasonic welding, and explosion welding, each with its own unique advantages and applications. For example, friction welding involves rotating one of the metal components against the other under pressure, generating heat through friction to create a bond. Overall, pressure welding offers a versatile and efficient method for joining metals, providing strong and durable bonds without the need for melting or additional filler material. The best advantage it has is the retention of the metallic properties of the base metal as it does not melt during joining.

Internal Defect

Internal defects in welding are imperfections that occur within the welded joint or base metal, which are not readily visible from the surface. These defects can significantly compromise the integrity, strength, and performance of the weld, potentially leading to structural failures or other safety hazards. Internal defects are typically detected through non-destructive testing (NDT) methods, such as radiographic testing, ultrasonic testing, magnetic particle inspection, or dye penetrant inspection. Some common types of internal defects in welding, along with their causes and detection methods are:

Lack of Fusion and Incomplete Penetration: Lack of fusion and incomplete penetration occur when the weld metal fails to fuse completely with the base metal or when it does not penetrate through the entire thickness of the joint. These defects can weaken the weld joint and reduce its load-bearing capacity. Lack of fusion and incomplete penetration can be caused by factors such as inadequate heat input, improper welding technique, or poor joint fit-up. Radiographic testing and ultrasonic testing are commonly used to detect these internal defects by providing detailed images of the weld cross-section, revealing any discontinuities or incomplete fusion zones.

Porosity: Porosity refers to the presence of gas pockets or voids within the weld metal. It can result from contaminants such as moisture, oil, or rust on the base metal, improper shielding gas, or incorrect welding parameters. It is one of the most common welding defects. It can weaken the weld joint and reduce its mechanical properties. According to the American Welding Society (AWS), porosity is primarily caused by the entrapment of gases such as hydrogen, oxygen, and nitrogen during the welding process (AWS, 2015). Sources of these gases include moisture, oil, rust, and contaminants on the surface of the base metal. Improper shielding gas coverage or gas flow rates can also contribute to porosity.

Undercut: Undercutting is a groove or depression along the weld toe or weld face, typically caused by excessive heat input or improper welding technique. It weakens the weld joint and increases the risk of failure. Undercutting can be caused by factors such as improper electrode angle, excessive welding speed, or insufficient filler metal (Jeffus, 2014). To prevent undercut, welders should maintain the correct welding parameters, electrode angle, and travel speed, as well as ensure proper joint preparation.

Inclusions: Inclusions are foreign materials trapped within the weld metal, such as slag, oxide, or dirt. They can impair the integrity and strength of the weld joint. Inclusions may occur due to inadequate cleaning of the base metal, improper fluxing, or insufficient shielding gas coverage. Ultrasonic testing and radiographic testing can detect inclusions by revealing irregularities or discontinuities within the weld cross-section.

Cracks: Cracks are discontinuities within the weld metal that can propagate and lead to catastrophic failure. They may result from factors such as high levels of residual stress, excessive cooling rates, or metallurgical issues. Ultrasonic testing, radiographic testing, and magnetic particle inspection are commonly used to detect cracks by identifying discontinuities or anomalies within the weld structure.

Liquefied Petroleum Gas: Liquefied Petroleum Gas (Liquefied Petroleum Gas) is a versatile and widely used fuel, essential in both domestic and industrial applications. Liquefied Petroleum Gas is a mixture of hydrocarbon gases, primarily propane (C3H8) and butane (C4H10), that are produced as byproducts during the refining of crude oil and the processing of natural gas. It is stored and transported in a liquid state under moderate pressure, making it a convenient and efficient energy source.

Properties of Liquefied Petroleum Gas

Liquefied Petroleum Gas is colorless and odorless in its natural state, but an odorant, usually ethyl mercaptan, is added to detect leaks. It is heavier than air, so it can accumulate in low-lying areas, posing a risk of explosion if ignited. Key properties of Liquefied Petroleum Gas include:

High Energy Content: Liquefied Petroleum Gas has a high calorific value, providing substantial energy output per unit.

Clean Burnin: It produces fewer pollutants compared to other fossil fuels, leading to lower emissions of carbon dioxide (CO2), nitrogen oxides (NOx), and sulfur oxides (SOx).

Versatility: It can be used for heating, cooking, automotive fuel (autogas), and various industrial processes.

Storage and Transportation: Liquefied Petroleum Gas can be stored in cylinders or bulk tanks and transported easily by road, rail, sea, or pipeline.

Empirical Studies

Table 1: Empirical Studies

S/N	Author(s)/Year	Literature/Study	Contribution/Result	Method Used	Gap/Gap Related Remarks
1	Attih et.al. (2022)	Assessment of risk exposure in oil and gas depots of Niger Delta, Nigeria	The study reported that accident risk is very high at most oil and gas facilities in Niger Delta	The study used cross sectional research design	The study failed to identify the risks and well as its major causes
2	Talouti et. al. (2022)	Numerical investigations of damage behaviour at the weld/base metal interface	The study reported that interface damage depending on shape and material properties of defects has an	Numerical simulations based on the finite element method	Causes were not identified in the study

			impact on pipeline safety and integrity.		
3	Ajibade & Oluwole (2018)	Factors affecting the integrity of oil and gas pipelines in Nigeria	The study reported that corrosion is a major cause of pipeline failure in Nigeria.	The study used cross sectional research design backed with secondary data	The used of mixed study is more appropriate for the study
4	Mgonja (2017)	The failure investigation of fuel storage tanks weld joints in Tanzania	The study stated that submerged arc welding and metal gas arc welding which allow for semi and full automated processes is the best method of welding fuel storage tank	The study used cross sectional research design with data obtained qualitatively.	The used of mixed study is more appropriate for the study
5	Achebe et. al. (2012)	Analysis of oil pipeline failures in the oil and gas industries in the Niger Delta area of Nigeria	The study reported that weld failure is a major cause of pipeline failure in Nigeria.	Qualitative study	The used of mixed study is more appropriate for the study

Hryciuk *etal.*(2017) examined girth weld integrity evaluation on a vintage gas pipeline. They discovered a leak on a girth weld transmission gas pipeline while recoating works were being performed. Failure analysis conducted showed that the leak was caused by a pre-existing defect in the girth weld which had not been evolving over time. They also observed that the link is caused as a result of particular stress condition to which the gas pipeline was subject during the recoating work, and the defect destabilized and causes progress failure. The main crux of their paper is that, they discover linkages/cracks as a major factor impeding pipeline integrity.

Dakhel *et al* (2023) investigated the behaviour of the girth welds and the reserves in the girth welds of operating pipelines. The study performed two tests, fatigue and burst tests. These tests were carried out on experimental pipeline sections. The two tests were carried out using the computer-controlled MTS-type electro-hydraulic testing system. While fatique test was performed at 100bar, the burst test was performed at 700bar. The study reported that both similarities and differences can be observed in the behavior of experimental full- scale pipe sections containing girth welds. Both the similarities and the differences depend on the geometrical dimensions of the pipe sections (outside diameter, wall thickness) and the strength category of the material of the pipes (X52, X60, X65). It recommended that both different types of the girth welds and girth welds with internal pressure and superimposed external load should be investigated.

Bao *etal.* (2022) investigated the specific causes of weld failure in shale gas gathering pipeline. To achieve this objective, the study carried out experimental analysis of the weld joints by means of Macroscopic detection, mechanics property analysis, metallographic analysis, scanning electron microscopy (SEM), energy spectrum analysis (EDS). The study reported that CO2 corrosion is the main cause of weld failure of flat shale gas gathering pipeline. In addition, there are obvious defects in the weld and large residual stress, coupled with the presence of Sulphur element, which directly aggravate the corrosion perforation of the weld. The study can be performed in a liquefied petroleum gas facility.

Methodology

This research employed a descriptive research design, combining various research methods and approaches to comprehensively investigate welding defects in Liquefied Petroleum Gas (LPG) distribution plants in Rivers State. The methodology flowchart is outlined Figure 1.

Sampling and Data Collection

Site Selection: Although all Liquefied Petroleum Gas (LPG) plants in Obio/Akpor Local Government Area were initially considered for inclusion in the study, only a select number were ultimately chosen. This selection was guided by specific eligibility criteria designed to ensure a representative sample. The criteria included the plant's age, size, and production capacity, allowing for a focused and meaningful analysis.

Sample Collection: Welded joints from different sections of the plants, including storage tanks, pipelines, and distribution points, were sampled. The samples were chosen based on visual indications of defects or corrosion.

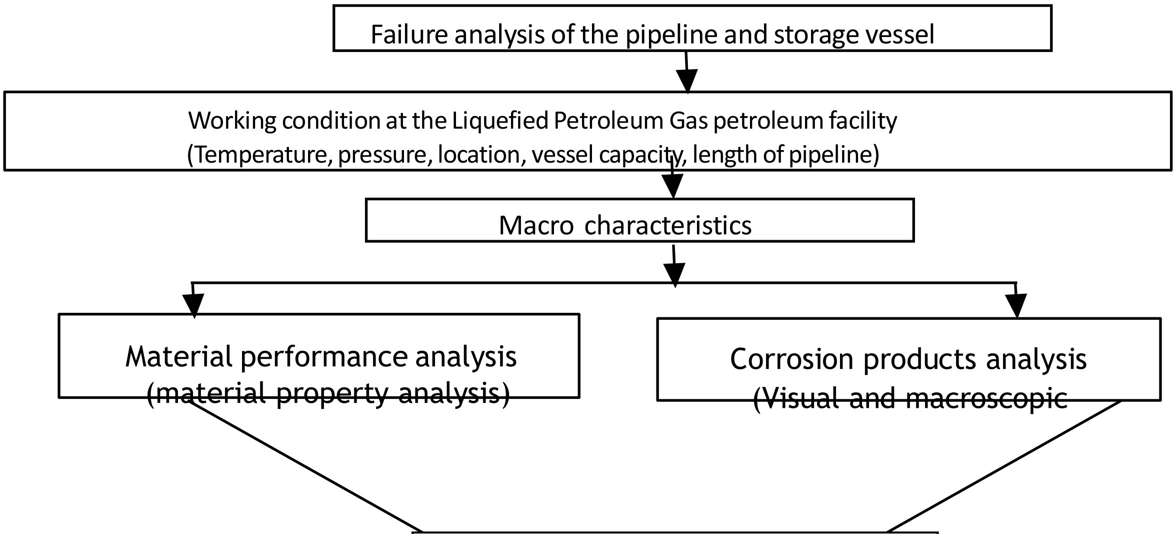

Figure: Methodology Flow chart

Inclusive Criteria

The following criteria was used to determine the Liquefied Petroleum Gas facility used for the study:

1. The facilities utilized for this study were exclusively liquefied petroleum gas (Liquefied Petroleum Gas) plants, each functioning as an independent, stand-alone entity. This means that these plants operate separately and are not integrated with other types of energy production or distribution systems.
2. Each facility included in the study is equipped with both storage and dispensing capabilities. These two components are interconnected by a network of pipelines, ensuring seamless transfer of Liquefied Petroleum Gas from the storage units to the dispensing units. The storage facilities typically consist of large tanks designed to hold the liquefied petroleum gas under pressure, while the dispensing facilities include pumps and nozzles used for filling containers or vehicles.
3. All the facilities selected for this study have been in continuous operation for a minimum of five years. This operational period indicates a level of established practice and reliability, allowing for a more robust analysis of their performance, safety protocols, and maintenance practices over a significant

duration.

Working conditions at the facilities/Maco characteristics
The working conditions at each facility was determined. This included the following:

1. **Average temperature and pressure:** the average working temperature and pressure at which the LPG is maintained in the storage vessels and pipelines was determined using the following Equations 3.1 and 3.2:

$$\text{Average temperature } (^{o}\text{C}) = \frac{\sum \text{daily temperature}}{\text{number of days}} \quad (3.1)$$

$$\text{Average pressure (Pa)} = \frac{\sum \text{daily pressure}}{\text{number of days}} \quad (3.2)$$

The daily working pressure and temperature at both the storage vessel and pipeline at each facility used for the study were collected from each facility record/maintenance books. The temperature and pressure record for the period of 30 days, April, 2024) was used for the calculation.

Material Performance Analysis
For the material performance analysis of the various welded joints present in both the storage vessels and the connecting pipelines, one analysis was performed.

Mechanics/Material Property Analysis
Mechanics and material property analysis involves assessing how materials behave under various mechanical loads and environmental conditions. It involves understanding various factors that affect the performance, strength, and reliability of the weld. To perform the mechanics and material property analysis of the welded joint, the following procedures were followed:

Material Properties Determination
The chemical composition of the base materials, heat-affected zone (HAZ), and the weld metals of all welded joints were determined using a hand-held X-Ray Fluorescence (XRF) device.

Weld Quality Examination
All the welded joints were examined for the presence of porosity, cracking, inclusions, undercut, overlap, and incomplete fusion. This was performed using a mobile X-ray machine to create digital images of the welded joints. Afterwards, the images were analyzed for the presence of the aforementioned welding defects.
Table 2: Details and description of LPG plants used for the study

Facility	Location	Number of welded joints considered in storages vessel (s)	pipeline infrastructure
LPG-GP-1	East West Road, Rumuekini	16 (one vessel)	8
LPG-GP-2	Aluu road Rumuekini	18 (one vessel)	5
LPG-GP-3	Ikwerre road, Rumodomaya	38 (3 vessels)	16
LPG-GP-4	East West Road, Ozuoba	14 (1 vessel)	8
LPG-GP-5	Mgbuoba	28 (2 vessels)	12

Table 3: Working conditions at the facilities

Facility	Storage			Pipeline infrastructure		
	Average Pressure (psi)	Average temperature (°C)	Capacity (MT)	Average Pressure (psi)	Average temperature (°C)	Length (m)
LPG-GP-1	116	15	12	16.3	25	75
LPG-GP-2	162	21	12	22.9	26	35
LPG-GP-3	209	27	24	50.6	31	120
LPG-GP-4	139	18	12	31.8	27	72
LPG-GP-5	193	25	36	26.7	25	96

Table 4: Welding process parameters

Parameter	Values
Welding current (I) (Ampere)	150
Welding voltage (V) (volts) Welding	
speed (S) (mm/min) Material	20
thickness (T) (mm)	1000
Shielding gas flow rate (F) (L/min)	5
	15

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Table 5: Details and description of LPG plants used for the study

Facility	Location	Number of welded joints considered in storages vessel(s)	Number of welded joints considered in pipeline infrastructure
LPG-GP-1	East West Road, Rumuekini	16 (one vessel)	8
LPG-GP-2	Aluu road Rumuekini	18 (one vessel)	5
LPG-GP-3	Ikwerre road, Rumodomaya	38 (3 vessels)	16
LPG-GP-4	East West Road, Ozuoba	14 (1 vessel)	8
LPG-GP-5	Mgbuoba	28 (2 vessels)	12

Table 6: Working conditions at the facilities

Facility	Storage			Pipeline infrastructure		
	Average Pressure (psi)	Average temperature (°C)	Capacity (MT)	Average Pressure (psi)	Average temperature (°C)	Length (m)
LPG-GP-1	116	15	12	16.3	25	75
LPG-GP-2	162	21	12	22.9	26	35
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LPG-GP-4	139	18	12	31.8	27	72
LPG-GP-5	193	25	36	26.7	25	96

Table 5 outlines the details and descriptions of the LPG plants used for the study, LPG-GP-3 has the highest complexity in both storage vessels and pipeline infrastructure followed by LPG-GP-5 that has a significant number of welded joints, especially in the storage vessels. LPG-GP-1, LPG-GP-2, and LPG-GP-4 have fewer welded joints, suggesting simpler and possibly more manageable infrastructure in terms of welding and joint integrity. Table 6 outlines the working conditions at the LPG plants used for the study; LPG-GP3 has the highest storage capacity and the longest pipeline, with moderate pressures and temperatures, making it suitable for large-scale operation. LPG-GP-4 and LPG-GP-2 have moderate conditions, with LPG-GP-1 has the lowest pressures and temperatures, indicating it might be suited for less demanding conditions.

Working Condition at the facilities/Macro characteristics

The working conditions at each facility was determined. This included the following:

1. Average working temperature and pressure: the average working temperature and pressure at which the LPG is maintained in the storage vessels and pipelines was determined using the following Equations 1 and 2:

$$\text{Average temperature } (^{\circ}\text{C}) = \frac{\sum \text{daily temperature}}{\text{number of days}} \quad (1)$$

$$\text{Average pressure (Pa)} = \frac{\sum \text{daily pressure}}{\text{number of days}} \quad (2)$$

The daily working pressure and temperature at both the storage vessel and pipeline at each facility used for the study were collected from each facility record/maintenance books. The temperature and pressure record for the period of 30 days, April, 2024) was used for the calculation.

3. **Storage vessel capacity:** the design capacity and effective capacity of the storage vessel(s) at each facility were determined. This was done by checking each facility DPR approval for the design capacity while the effective capacity was determined by checking each facility supply and stock manifest to determine the peak storage at each facility.
4. **Location and Site Design:** although all the Liquefied Petroleum Gas facilities used for the study are situated in Obio/Akpor LGA, Rivers State, the various locations of these facilities in study area were recorded. Also, the design of each facility included in the study was also recorded and reported in the result section of this study.
5. **Maintenance and Monitoring:** for all the facilities used for the study, their routine inspections procedures and practices, equipment maintenance procedures and practices, and predictive maintenance procedures and practices documents were obtained and used for analysis.

Material Performance Analysis

For the material performance analysis of the various welded joints present in both the storage vessels and the connecting pipelines, one analysis was performed.

Mechanics and material property analysis

Mechanics and material property analysis involves assessing how materials behave under various mechanical loads and environmental conditions. It involves understanding various factors that affect the performance, strength, and reliability of the weld. To perform the mechanics and material property analysis of the welded joint, the following procedures were followed:

Material Properties Determination
The chemical composition of the base materials, heat-affected zone (HAZ), and the weld metals of all welded joints were determined using a hand-held X-Ray Fluorescence (XRF) device.

Weld Quality Examination
All the welded joints were examined for the presence of porosity, cracking, inclusions, undercut, overlap, and incomplete fusion. This was performed using a mobile X-ray machine to create digital images of the welded joints. Afterwards, the images were analyzed for the presence of the aforementioned welding defects.

Table 7: Monitoring procedure/routine of welded joints at the facilities

Facility	Storage vessels						Pipeline infrastructure					
	Welded joints Leak	Welded joints Corrosion	Welded joints Integrity	Pressure	Temperature	Physical damage (cracking, discoloration, deformation)	Welded joints Leak	Welded joints Corrosion	Welded joints Integrity	Pressure	Temperature	Physical damage (cracking, discoloration, deformation)
LPG-GP-1	Weekly	Weekly	Yearly	Daily	Daily	Yearly	Monthly	Monthly	Yearly	When needed	When needed	Yearly
LPG-GP-2	Yearly	Yearly	Yearly	Every three days	Every three days	Yearly	Yearly	Yearly	Yearly	When needed	When needed	Yearly
LPG-GP-3	Yearly	Yearly	Yearly	Daily	Daily	Yearly	Yearly	Yearly	Yearly	Weekly	Weekly	N/A
LPG-GP-4	Yearly	Yearly	Yearly	Daily	Daily	Yearly	Yearly	Yearly	Yearly	Routinely	Routinely	N/A
LPG-GP-5	Yearly	Yearly	Yearly	Daily	Daily	Yearly	Yearly	Yearly	Yearly	Routinely	Routinely	N/A

Table 8: Maintenance procedure/routine of welded joints at the facilities

Facility	Storage vessels						Pipeline infrastructure					
	Painting of welded joints	Replacement of welded joints	Removal of dirt, debris and corrosive materials on welded joints	Ultrasonic Testing of welded joints	Radioactive testing of welded joints	Magnetic testing of welded joints	Painting of welded joints	Replacement of welded joints	Removal of dirt, debris and corrosive materials on welded joints	Ultrasonic Testing of welded joints	Radioactive testing of welded joints	Magnetic testing of welded joints
LPG-GP-1	When needed	When needed	Monthly	N/A	N/A	N/A	When needed	When needed	Monthly	N/A	N/A	N/A
LPG-GP-2	When needed	When needed	Monthly	N/A	N/A	N/A	When needed	When needed	Monthly	N/A	N/A	N/A
LPG-GP-3	When needed	When needed	Monthly	N/A	N/A	N/A	When needed	When needed	Monthly	N/A	N/A	N/A
LPG-GP-4	When needed	When needed	Monthly	N/A	N/A	N/A	When needed	When needed	Monthly	N/A	N/A	N/A
LPG-GP-5	When needed	When needed	Monthly	N/A	N/A	N/A	When needed	When needed	Monthly	N/A	N/A	N/A

Table 9: Material Performance Analysis of storage vessel welded joints at facility LPG-GP-1

Element/Composition	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	6 (%)	7 (%)	8 (%)	9 (%)	ASME (%)
Base Material composition										
Fe	98	98.0	68.0	97.5	89.0	65.0	97.8	98.2	98.0	97.5-98.5
C	0.1	0.25	18.0	1.0	6.0	23.0	0.1	0.1	0.1	0.08-0.12
Mn	0.8	0.6	11.0	0.6	4.0	4.5	0.9	0.8	0.8	0.7-1
Si	0.3	0.3	2.5	0.5	0.25	3.0	0.3	0.3	0.3	0.2-0.4
P	0.01	0.04	0.8	0.4	0.1	0.18	0.03	0.02	0.02	>0.02
S	0.01	0.05	0.03	0.02	0.02	0.03	0.03	0.02	0.02	>0.02
Cr	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3-0.5
Ni	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2-0.4
HAZ composition										
Fe	97.90	97.5	67.5	97.3	88.5	64.5	97.9	97.7	97.8	97.5-98.5
C	0.12	0.30	17.5	0.9	5.8	22.5	0.11	0.12	0.1	0.08-0.12
Mn	0.85	0.65	10.8	0.5	3.8	4.3	0.9	0.8	0.8	0.70-1
Si	0.32	0.35	2.3	0.4	0.23	2.8	0.3	0.3	0.3	0.2-0.4
P	0.01	0.03	0.7	0.3	0.09	0.15	0.03	0.02	0.02	>0.02
S	0.01	0.04	0.02	0.01	0.02	0.01	0.03	0.02	0.02	>0.02
Cr	0.42	0.3	0.3	0.4	0.5	0.4	0.4	0.4	0.4	0.3-0.5
Ni	0.31	0.4	0.4	0.2	0.3	0.4	0.3	0.3	0.3	0.2-0.4
Weld Metal composition										
Fe	97.8	98.2	69.0	97.7	89.2	65.5	97.7	97.8	97.8	97-98
C	0.11	0.28	18.5	1.2	6.2	22.8	0.1	0.1	0.1	0.08-0.12
Mn	1	0.7	11.5	0.7	0.7	4.7	0.9	0.8	0.8	0.8-1.2
Si	0.35	0.4	2.8	0.6	0.6	3.2	0.3	0.3	0.3	0.2-0.4
P	0.01	0.03	0.9	0.4	0.4	0.18	0.02	0.02	0.02	>0.02
S	0.01	0.03	0.03	0.02	0.02	0.03	0.03	0.02	0.02	>0.02
Cr	0.45	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3-0.5
Ni	0.35	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2-0.4

Table 10: Material Performance Analysis of storage vessel welded joints at facility LPG-GP-2

Element/Composition	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	6 (%)	7 (%)	8 (%)	9 (%)	ASME (%)
Base Material composition										
Fe	98.1	97.6	98.3	98.0	97.9	97.7	98.2	98.4	97.8	97.5-98.5
C	0.10	0.11	0.09	0.12	0.08	0.10	0.09	0.11	0.10	0.08-0.12
Mn	0.9	0.8	0.7	0.9	1.0	0.8	0.9	0.7	1.0	0.7-1
Si	0.3	0.4	0.2	0.3	0.4	0.2	0.3	0.4	0.3	0.2-0.4
P	0.01	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.02	>0.02
S	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	>0.02
Cr	0.4	0.3	0.5	0.4	0.3	0.4	0.3	0.5	0.4	0.3-0.5
Ni	0.3	0.4	0.2	0.3	0.4	0.2	0.3	0.4	0.3	0.2-0.4
HAZ composition										
Fe	98.0	97.9	98.1	98.2	97.8	98.1	97.9	98.0	98.1	97.5-98.5
C	0.11	0.10	0.09	0.12	0.08	0.10	0.09	0.11	0.10	0.08-0.12
Mn	0.9	0.7	0.8	1.0	0.7	0.9	0.8	0.9	1.0	0.70-1
Si	0.3	0.4	0.2	0.3	0.4	0.2	0.3	0.4	0.3	0.2-0.4
P	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.02	>0.02
S	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	>0.02
Cr	0.3	0.4	0.3	0.5	0.3	0.4	0.3	0.4	0.3	0.3-0.5
Ni	0.3	0.4	0.2	0.3	0.2	0.4	0.3	0.4	0.2	0.2-0.4
Weld Metal composition										
Fe	97.5	97.8	97.9	97.7	97.4	97.6	97.8	97.5	97.9	97-98
C	0.09	0.11	0.08	0.12	0.10	0.08	0.11	0.09	0.10	0.08-0.12
Mn	1.0	1.1	0.9	0.8	1.2	1.0	1.1	0.9	0.8	0.8-1.2
Si	0.3	0.4	0.2	0.3	0.4	0.2	0.3	0.4	0.3	0.2-0.4
P	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.01	>0.02
S	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.02	>0.02
Cr	0.4	0.3	0.5	0.3	0.4	0.5	0.4	0.3	0.5	0.3-0.5
Ni	0.4	0.3	0.2	0.4	0.2	0.3	0.4	0.2	0.3	0.2-0.4

Table 10 is the analysis table of the welding joints monitoring procedure and routine applicable at all the gas plants used for the study. LPG-GP-1 has the most frequent checks for leaks and corrosion in both storage vessels and pipeline infrastructure. It also performs daily checks for pressure and temperature in storage vessels, which indicates a rigorous monitoring routine. LPG-GP-3 performs daily checks for pressure and temperature in storage vessels and weekly checks in pipeline infrastructure, showing a high level of diligence in monitoring operational parameters. LPG-GP-4 and LPG-GP-5 have similar monitoring routines with daily checks for storage vessels' pressure and temperature and routine checks for pipeline infrastructure. LPG-GP-2 has less frequent checks for storage vessels (every three days for pressure and temperature) and yearly checks for most parameters, indicating a less frequent monitoring schedule compared to others.

For maintenance data, presented in Table 10, all the facilities follow a similar routine for the maintenance of welded joints, which includes painting and replacement when needed, and monthly removal of dirt, debris, and corrosive materials. However, none of the facilities employ ultrasonic, radioactive, or magnetic testing for welded joints in either storage vessels or pipeline infrastructure. Based on the detailed analysis of monitoring procedures, working conditions, and maintenance routines: LPG-GP-3 appears robust in handling high pressures and temperatures with rigorous daily monitoring of storage vessel parameters and routine checks of pipeline infrastructure. LPG-GP-5 stands out for its high storage capacity and the longest pipeline, combined with frequent monitoring routines, indicating it can handle large-scale and potentially high-risk operations.

LPG-GP-1 exhibits the most frequent checks for leaks and corrosion, showing a high level of diligence in maintenance practices. LPG-GP-2 and LPG-GP-4 follow less frequent monitoring routines, but their maintenance practices are consistent with other facilities.

Table 11: Material Performance Analysis of storage vessel welded joints at facility LPG-GP-3

Element/Composition	Fe	C	Mn	Si	P	S	Cr	Ni
			Base Material composition					
Welded joint 1 (%)	97.0	0.07	0.6	0.15	0.01	0.01	0.25	0.15
Welded joint 2 (%)	97.2	0.06	0.65	0.18	0.015	0.018	0.28	0.19
Welded joint 3 (%)	96.9	0.07	0.66	0.16	0.02	0.017	0.27	0.18
Welded joint 4 (%)	97.1	0.06	0.68	0.17	0.015	0.015	0.26	0. 16
Welded joint 5 (%)	97.0	0.07	0.67	0.19	0.01	0.02	0.24	0.17
Welded joint 6 (%)	96.8	0.06	0.69	0.16	0.015	0.017	0.23	0.18
Welded joint 7 (%)	97.1	0.07	0.68	0.18	0.02	0.02	0.27	0.16
Welded joint 8 (%)	97.0	0.06	0.67	0.19	0.015	0.015	0.25	0.17
Welded joint 9 (%)	96.9	0.07	0.65	0.15	0.02	0.017	0.26	0.16
Welded joint 10 (%)	97.0	0.06	0.68	0.18	0.01	0.02	0.24	0.17
Welded joint 11 (%)	97.2	0.07	0.69	0.19	0.015	0.015	0.25	0.18
Welded joint 12 (%)	97.1	0.06	0.66	0.16	0.02	0.017	0.27	0.16
Welded joint 13 (%)	96.8	0.07	0.65	0.19	0.01	0.02	0.26	0.17
Welded joint 4 (%)	97.0	0.06	0.67	0.15	0.015	0.015	0.23	0.18
Welded joint 15 (%)	96.9	0.07	0.68	0.16	0.02	0.017	0.24	0.16
Welded joint 16 (%)	97.1	0.06	0.66	0.18	0.01	0.02	0.25	0.17
Welded joint 17 (%)	97.0	0.07	0.65	0.19	0.015	0.015	0.26	0.18
Welded joint 18 (%)	96.8	0.06	0.67	0.15	0.02	0.017	0.23	0.16
Welded joint 19 (%)	97.0	0.07	0.68	0.19	0.01	0.02	0.24	0.17
Welded joint 10 (%)	97.1	0.06	0.66	0.16	0.015	0.015	0.25	0.18
Welded joint 21 (%)	97.0	0.07	0.67	0.19	0.02	0.02	0.27	0.16
Welded joint 22 (%)	96.9	0.06	0.65	0.15	0.015	0.017	0.26	0.17
Welded joint 23 (%)	97.0	0.07	0.68	0.18	0.01	0.015	0.24	0.16
Welded joint 24 (%)	97.1	0.06	0.67	0.19	0.02	0.02	0.25	0.17
Welded joint 25 (%)	96.8	0.07	0.66	0.15	0.015	0.017	0.23	0.18
Welded joint 26 (%)	97.0	0.06	0.68	0.18	0.01	0.02	0.24	0.16
Welded joint 27 (%)	97.1	0.07	0.66	0.19	0.015	0.015	0.25	0.17
ASME standard (%)	97.5-98.5	.08-.12	0.7-1	0.2-0.4	>0.02	>0.02	.3-.5	.2-.4
			HAZ composition					
Welded joint 1 (%)	97.2	0.07	0.68	0.18	0.01	0.02	0.26	0.17
	97.1	0.06	0.67	0.19	0.015	0.017	0.25	0.18
	96.9	0.07	0.65	0.15	0.02	0.015	0.27	0.16
	97.0	0.06	0.66	0.16	0.015	0.02	0.24	0.17
	97.1	0.07	0.65	0.19	0.01	0.017	0.23	0.16
	97.0	0.06	0.68	0.15	0.02	0.02	0.26	0.18
	96.9	0.07	0.67	0.19	0.01	0.015	0.24	0.17
	97.0	0.06	0.66	0.18	0.015	0.02	0.25	0.16
	97.2	0.07	0.65	0.16	0.01	0.015	0.26	0.18
	97.1	0.06	0.67	0.19	0.015	0.02	0.23	0.17
	97.0	0.07	0.66	0.15	0.02	0.017	0.24	0.18
	96.9	0.06	0.68	0.16	0.01	0.015	0.27	0.17
	97.1	0.07	0.67	0.19	0.015	0.02	0.25	0.16
	97.0	0.06	0.65	0.18	0.01	0.017	0.23	0.18
	97.2	0.07	0.66	0.15	0.015	0.02	0.26	0.17
	97.1	0.06	0.68	0.16	0.02	0.015	0.25	0.18
	97.0	0.07	0.67	0.19	0.01	0.02	0.24	0.17
	96.9	0.06	0.66	0.18	0.015	0.017	0.23	0.16
	97.1	0.07	0.65	0.19	0.02	0.015	0.27	0.18
	97.0	0.06	0.68	0.15	0.015	0.02	0.26	0.17

Welded joint 2 (%)
Welded joint 3 (%)
Welded joint 4 (%)
Welded joint 5 (%)
Welded joint 6 (%)
Welded joint 7 (%)
Welded joint 8 (%)
Welded joint 9 (%)
Welded joint 10 (%)
Welded joint 11 (%)
Welded joint 12 (%)
Welded joint 13 (%)
Welded joint 4 (%)
Welded joint 15 (%)
Welded joint 16 (%)
Welded joint 17 (%)
Welded joint 18 (%)
Welded joint 19 (%)
Welded joint 10 (%)
Welded joint 21 (%)
Welded joint 22 (%)
Welded joint 23 (%)
Welded joint 24 (%)
Welded joint 25 (%)
Welded joint 26 (%)
Welded joint 27 (%)
ASME standard (%)

Welded joint 1 (%)
Welded joint 2 (%)
Welded joint 3 (%)
Welded joint 4 (%)
Welded joint 5 (%)
Welded joint 6 (%)
Welded joint 7 (%)
Welded joint 8 (%)
Welded joint 9 (%)
Welded joint 10 (%)
Welded joint 11 (%)
Welded joint 12 (%)
Welded joint 13 (%)
Welded joint 14 (%)
Welded joint 15 (%)
Welded joint 16 (%)
Welded joint 17 (%)
Welded joint 18 (%)
Welded joint 19 (%)
Welded joint 10 (%)
Welded joint 21 (%)
Welded joint 22 (%)
Welded joint 23 (%)
Welded joint 24 (%)
Welded joint 25 (%)
Welded joint 26 (%)
Welded joint 27 (%)
ASME standard (%)

97.2	0.07	0.66	0.18	0.01	0.015	0.25	0.16
97.1	0.06	0.65	0.19	0.015	0.02	0.24	0.18
97.0	0.07	0.67	0.15	0.02	0.015	0.23	0.17
96.9	0.06	0.68	0.18	0.015	0.02	0.27	0.18
97.0	0.07	0.66	0.19	0.01	0.015	0.26	0.17
97.1	0.06	0.65	0.15	0.02	0.02	0.25	0.16
97.2	0.07	0.68	0.16	0.015	0.015	0.24	0.18
97.5-98.5	.08-.12	0.7-1	0.2-0.4	>0.02	>0.02	.3-.5	.2-.4
Weld Metal composition							
96.5	0.07	0.75	0.18	0.015	0.02	0.26	0.18
96.8	0.06	0.77	0.19	0.01	0.017	0.28	0.17
96.7	0.07	0.76	0.16	0.015	0.015	0.27	0.18
96.9	0.06	0.75	0.17	0.02	0.02	0.25	0.16
96.8	0.07	0.78	0.15	0.015	0.017	0.23	0.17
96.7	0.06	0.76	0.18	0.02	0.015	0.26	0.16
96.9	0.07	0.75	0.19	0.015	0.02	0.24	0.18
96.8	0.06	0.77	0.16	0.01	0.015	0.25	0.17
96.7	0.07	0.76	0.15	0.015	0.02	0.27	0.18
96.9	0.06	0.75	0.18	0.02	0.015	0.26	0.16
96.8	0.07	0.77	0.19	0.01	0.02	0.25	0.17
96.7	0.06	0.78	0.15	0.015	0.015	0.24	0.18
96.9	0.07	0.75	0.16	0.02	0.02	0.26	0.17
96.8	0.06	0.77	0.15	0.015	0.017	0.23	0.18
96.7	0.07	0.76	0.19	0.02	0.02	0.27	0.16
96.9	0.06	0.75	0.18	0.015	0.017	0.25	0.18
96.8	0.07	0.78	0.15	0.01	0.02	0.26	0.17
96.7	0.06	0.77	0.16	0.015	0.015	0.24	0.18
96.9	0.07	0.75	0.15	0.02	0.02	0.23	0.17
96.8	0.06	0.76	0.18	0.015	0.015	0.27	0.18
96.7	0.07	0.75	0.16	0.01	0.02	0.26	0.17
96.9	0.06	0.78	0.15	0.02	0.017	0.25	0.18
96.8	0.07	0.77	0.19	0.015	0.02	0.24	0.17
96.7	0.06	0.76	0.15	0.01	0.015	0.27	0.18
96.9	0.07	0.75	0.18	0.02	0.02	0.26	0.17
96.8	0.06	0.77	0.19	0.015	0.015	0.25	0.18
96.7	0.07	0.75	0.15	0.01	0.02	0.27	0.16
97-98	.08-.12	.8-1.2	.2-.4	>0.02	>0.02	.3-.5	.2-.4

Table 12: Material Performance Analysis of pipeline infrastructure welded joints at facility LPG-GP-5

Element/ Composition	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	6 (%)	7 (%)	8 (%)	9 (%)	10	11	12	ASME (%)
Base Material composition													
Fe	97.4	98.6	97.3	98.7	97.2	98.8	97.1	98.9	98.2	97.9	98.3	97.7	97.5-98.5
C	0.07	0.13	0.14	0.07	0.13	0.07	0.14	0.13	0.08	0.12	0.09	0.09	0.08-0.12
Mn	0.6	1.1	0.6	1.1	0.5	1.2	0.5	1.2	0.8	0.7	0.9	0.9	0.7-1
Si	0.1	0.5	0.1	0.5	0.6	0.1	0.5	0.1	0.2	0.3	0.4	0.3	0.2-0.4
P	0.02	0.03	0.04	0.02	0.03	0.04	0.02	0.04	0.018	0.017	0.019	0.03	>0.02
S	0.02	0.03	0.04	0.02	0.03	0.04	0.02	0.04	0.018	0.017	0.019	0.03	>0.02
Cr	0.2	0.6	0.2	0.6	0.7	0.2	0.6	0.2	0.3	0.4	0.5	0.4	0.3-0.5
Ni	0.1	0.5	0.1	0.5	0.6	0.1	0.5	0.1	0.2	0.3	0.4	0.2	0.2-0.4
HAZ composition													
Fe	97.4	98.6	97.3	98.7	97.2	98.8	97.1	98.9	97.9	98.0	97.5	97.7	97.5-98.5
C	0.07	0.13	0.14	0.07	0.13	0.07	0.14	0.13	0.11	0.09	0.1	0.11	0.08-0.12
Mn	0.6	1.1	0.6	1.1	0.5	1.2	0.5	1.2	0.9	0.7	0.9	0.8	0.7-1
Si	0.1	0.5	0.1	0.5	0.6	0.1	0.5	0.1	0.4	0.3	0.2	0.3	0.2-0.4
P	0.02	0.03	0.04	0.02	0.03	0.04	0.02	0.04	0.02	0.02	0.03	0.03	>0.02
S	0.02	0.03	0.04	0.02	0.03	0.04	0.02	0.04	0.02	0.02	0.03	0.03	>0.02
Cr	0.2	0.6	0.2	0.6	0.7	0.2	0.6	0.2	0.5	0.4	0.3	0.4	0.3-0.5
Ni	0.1	0.5	0.1	0.5	0.6	0.1	0.5	0.1	0.3	0.2	0.3	0.2	0.2-0.4
Weld Metal composition													
Fe	96.9	98.1	96.8	98.2	96.7	98.3	96.6	98.4	97.5	97.3	97.6	97.4	97-98
C	0.07	0.13	0.14	0.07	0.13	0.07	0.14	0.13	0.1	0.1	0.1	0.11	0.08-0.12
Mn	0.7	1.3	0.7	1.3	0.6	1.4	0.6	1.4	1.0	0.9	1.1	1.0	0.8-1.2
Si	0.1	0.5	0.1	0.5	0.6	0.1	0.5	0.1	0.2	0.3	0.3	0.4	0.2-0.4
P	0.02	0.03	0.04	0.02	0.03	0.04	0.02	0.04	0.03	0.02	0.02	0.03	>0.02
S	0.02	0.03	0.04	0.02	0.03	0.04	0.02	0.04	0.03	0.02	0.02	0.03	>0.02
Cr	0.2	0.6	0.2	0.6	0.7	0.2	0.6	0.2	0.3	0.4	0.4	0.5	0.3-0.5
Ni	0.1	0.5	0.1	0.5	0.6	0.1	0.5	0.1	0.2	0.4	0.3	0.2	0.2-0.4

Table 8-12 present the results of the material analysis of all the pipeline infrastructure welded joints of the sampled gas distribution plants; each table includes compositions of base materials, heat-affected zones (HAZ), and weld metals, along with ASME standards for comparison. For the base metal, all the joints examined consists of high percentages of iron (Fe), with minor variations in carbon (C), manganese (Mn), silicon (Si), phosphorus (P), sulfur (S), chromium (Cr), and nickel (Ni). The high and consistent iron content across all facilities which indicate a reliable base material for pipeline infrastructure. Furthermore, the composition of the other elements is consistent with ASME standards. These elements are crucial for determining mechanical properties and corrosion resistance.

For HAZ zone, the composition of elements is different from that of the base metal which is indicative of minimal alteration in chemical properties post-welding in the heat-affected zone. However, the changes are minimal and are also within ASME standards. Furthermore, the weld metal composition shows significant adjustments in composition compared to base materials and HAZ to achieve desired mechanical and metallurgical properties, particularly in carbon content (C), manganese (Mn), and alloying elements like chromium (Cr) and nickel (Ni). Generally, all the compositions align with ASME standards, ensuring the materials meet specified mechanical and chemical requirements for pipeline construction.

Model Result

The feasibility of the developed model was insisted by the use of data collected from the liquefied gas distribution facilities in Rivers State and also a liquefied oil and gas company. The values of welding process parameters stated in the chapter three used for determining Heat Input (HI) of the welding process, Cooling Rate (CR) of the welded joint and Shielding Gas Effectiveness (SGE) in Equations (1) and (2) and using the welding defect evaluation model for liquefied gas distribution facilities. The results obtained were employed to assess the existing welding defects in Liquefied gas distribution facilities by analyzing the quality of the weld section as per the calculated parameters.

Table 11: Computed values of welding process parameters

Parameters	Values
heat input (HI) of the welding process(kJ/mm)	0.3
cooling rate (CR) of the welded joint(kJ/mm^2)	0.36
Shielding gas effectiveness (SGE) (%)	75

Table 13: Computed values for welding process parameters

Parameters	Values
Residual stress in the (Mpa)	00117
Defect formation rate	2.65

Table 14: Calculated values for β, λ and Se

Parameters	Values
β (Coefficient of weld quality representing the overall quality of the welding process)	0.72
λ (Coefficient of defect severity representing the relative severity of a particular welding defect)	0.2
Se (effective structural capacity reduced by the presence of defects)	20

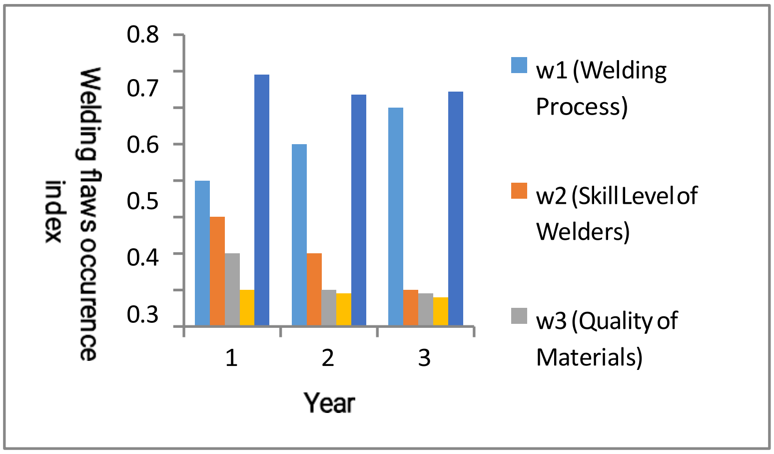

Figure 2: Increasing the value of w1 and decreasing the values of w2, w3 and w4

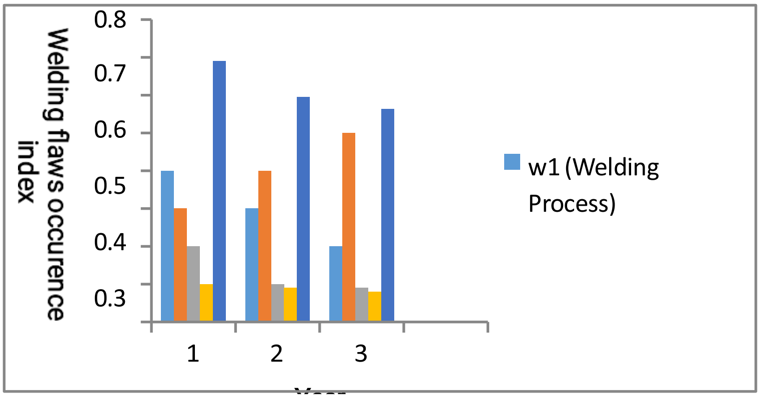

Figure 3: Increasing the value of w2 and decreasing the values of w1, w3 and w4

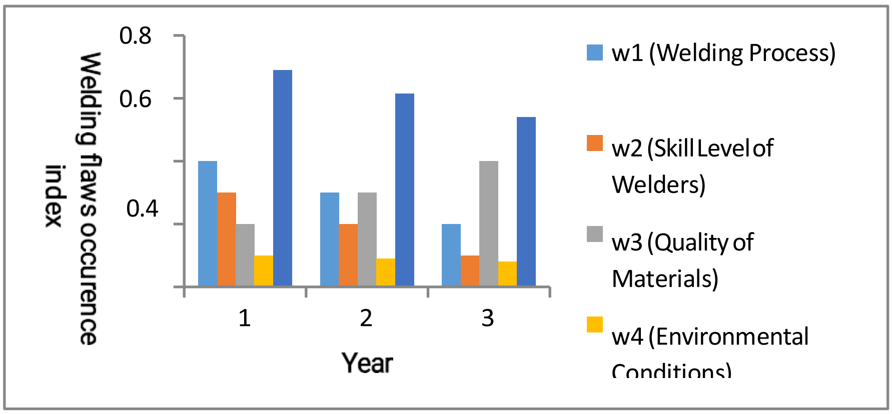

Figure 4: Increasing the value of w3 and decreasing the values of w1, w2, and w4

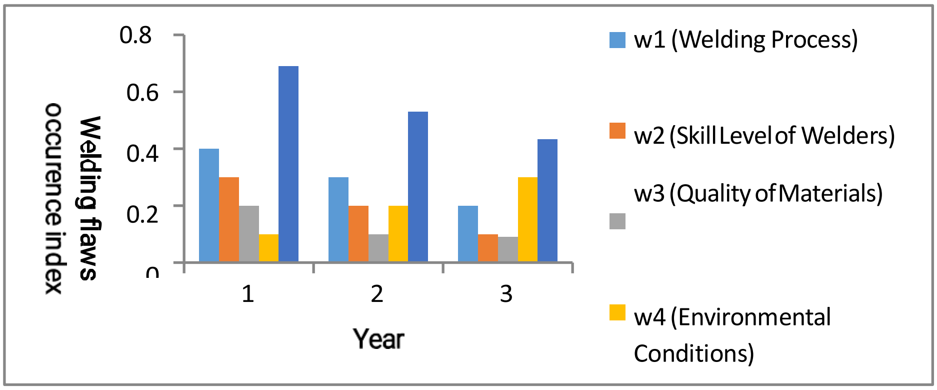

Figure 5: Increasing the value of w4 and decreasing the values of w1, w2 and w3

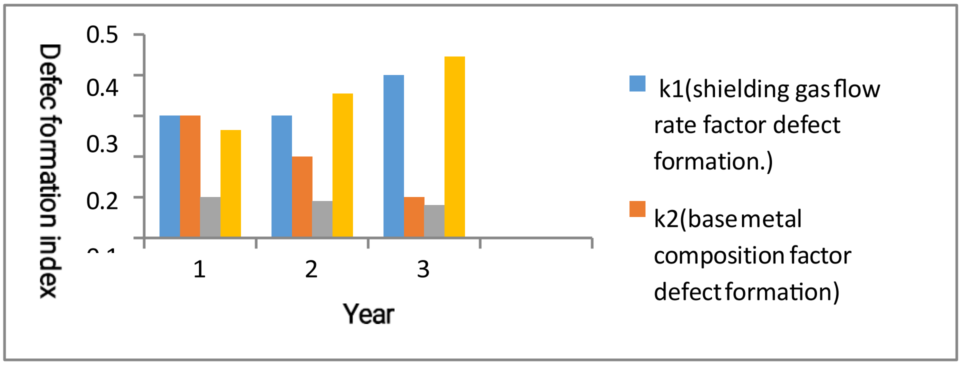

Figure 6: Increasing the value of k1 and decreasing the values of k2 and k3

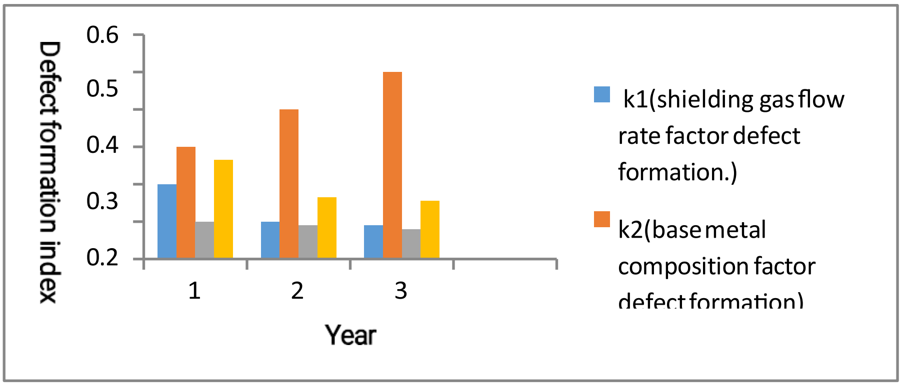

Figure 7: Increasing the value of k2 and decreasing the values of k1 and k3

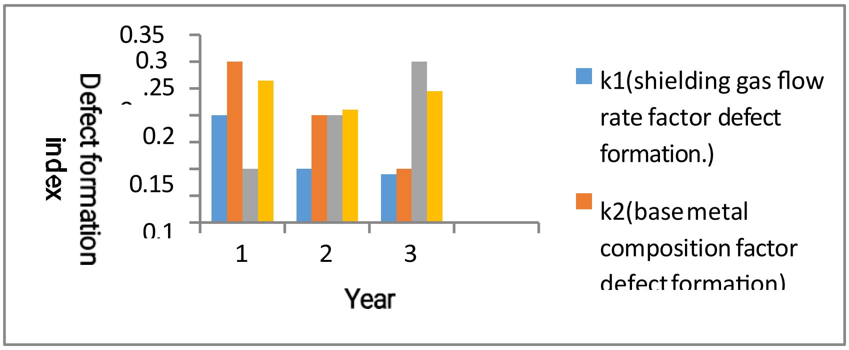

Figure 8: Increasing the value of k3 and decreasing the values of k1 and k2

DISCUSSION OF FINDINGS

Prevalence and distribution of welding defects within different components of Liquefied gas distribution facilities in Rivers State

The objective of examining the prevalence and distribution of welding defects within different components of liquefied gas distribution facilities is crucial for understanding the specific vulnerabilities within these infrastructures. This insight is necessary to develop targeted maintenance and inspection strategies, thereby enhancing safety and operational efficiency. The study revealed that surface roughness and surface cracks are particularly prevalent in storage vessel welding joints, while a broader range of defects, including surface and internal cracks, surface roughness, and undercuts, are commonly found in pipeline infrastructure.

Surface roughness refers to the irregularities on the surface of welded joints, which can result from inconsistent welding speed, poor welding technique, or contamination. Rough surfaces can increase the likelihood of corrosion by providing more surface area and micro-crevices where corrosive agents can accumulate. They also adversely affect the structural integrity and aesthetic quality of the storage vessels. The study indicated a high prevalence of surface roughness in the welded joints of storage vessels across multiple facilities. This suggests variability in welding quality and potentially suboptimal welding practices. Surface cracks is also prevalent in the storage vessels welded joints. Theses are discontinuities that appear on the surface of welded joints. They can be caused by improper cooling rates, residual stresses, or inadequate welding techniques. Surface cracks can serve as initiation points for more severe types of corrosion and can propagate under operational stresses, potentially leading to leaks or structural failure. The presence of surface cracks in storage vessel welding joints highlights areas where welding techniques might have been insufficient or where operational stresses are higher. The prevalence and distribution of welding defects within the different components of liquefied gas distribution facilities in Rivers State highlight critical areas for improvement in welding practices, inspection methods, and maintenance routines. Addressing these defects through enhanced training, rigorous quality control, and adherence to standards can significantly improve the safety, reliability, and efficiency of LPG distribution infrastructure. Future efforts should focus on adopting advanced technologies and preventive maintenance strategies to mitigate the risks associated with welding defects.

Root causes of these welding defects

Investigating the root causes of welding defects in liquefied gas distribution facilities is essential to developing effective mitigation strategies. By understanding the underlying factors contributing to defects such as surface roughness, cracks, and undercuts, facilities can implement targeted improvements in welding practices, material selection, maintenance routines, and environmental control. The major causes of welding defects at LPG facilities in Rivers State, as revealed by this study, can be traced to material properties, wrong welding techniques, improper maintenance techniques, and environmental conditions.

In the context of material selection for welding processes, the properties of the materials play a crucial role in determining the quality of welds and the occurrence of defects. The choice of materials that do not meet specified standards can lead to various welding defects, such as cracks and undercuts. For instance, inadequate carbon content in materials can result in brittleness, while excessive carbon content can lead to hardness and increased susceptibility to cracks (Shanmugasundar et al., 2023). Furthermore, using materials with incompatible properties for welding can result in poor weld quality and defects. Welding dissimilar metals without appropriate techniques can cause metallurgical incompatibilities and defects (Li-hua et al., 2023). Studies have emphasized the significance of selecting the appropriate filler material to achieve desired microstructural and mechanical properties in welded joints (Shanmugasundar et al., 2023). The choice of wire type has also been highlighted as a factor that can significantly impact weld quality (Li-hua et al., 2023). Additionally, the effects of different electrode types on the mechanical properties of welded materials have been studied, emphasizing the importance of proper selection of welding parameters for obtaining good weld quality (Aytekin et al., 2020). Moreover, research has shown that incomplete slag removal before welding or improper selection of welding materials can lead to defects such as slag inclusion in welded metal materials (Ren, 2022). Proper selection of both welding parameters and micro-jet cooling parameters has been identified as crucial for achieving the desired steel structure in welding processes (Piwnik et al., 2018). The influence of material grade, weld quality, and fabrication procedures on the structural durability of welded vehicle structures has been highlighted, underscoring the importance of material selection in welding applications (Barsoum et al., 2012). The selection of appropriate materials for welding processes is essential to ensure the quality and integrity of welded joints. Understanding the properties of materials and their compatibility for welding applications is vital in preventing defects and ensuring the reliability of welded components in various industries

In the context of welding technique, the selection and application of appropriate welding parameters are crucial in ensuring the quality of welds and minimizing defects. Incorrect welding parameters, such as heat input, welding speed, and electrode type, can lead to various welding defects. For instance, excessive heat input during welding can result in warping and internal stresses, which may lead to the formation of cracks (Fei et al., 2019). Inadequate skills or failure to adhere to welding procedures can also contribute to defects. Inconsistent welding speed and poor electrode handling, for example, can cause surface roughness and undercuts (Nguyen et al., 2006). Furthermore, insufficient preparation of the weld area, such as inadequate cleaning or poor fit-up, can result in defects like inclusions and porosity in the weld (Ren, 2022). Research has shown that optimizing welding techniques and parameters is essential to reduce crack formation during the welding of alloys (Böttger et al., 2020). Understanding the impact of heat input on weld formation and mechanical properties is crucial for optimizing welding procedures (Fei et al., 2019). Additionally, the selection of appropriate welding parameters can influence the microstructure-related properties, mechanical properties, and corrosion resistance of welds (Jeng et al., 2020). Moreover, the prevention of weld defects such as undercuts requires a deep understanding of their formation mechanisms and the influence of various process parameters (Zong et al., 2017). Furthermore, the effects of water flow on underwater wet welded steel have been studied to address defects like spatter, porosity, and undercuts (Surojo et al., 2021). In conclusion, the proper selection and control of welding parameters are essential for achieving high-quality welds and minimizing defects in welding processes. By understanding the impact of parameters such as heat input, welding speed, and electrode type, and adhering to best practices, welders can enhance the integrity and reliability of welded components in various applications.

For improper maintenance techniques, mmaintenance practices are crucial in preventing the propagation and exacerbation of welding defects. Neglecting regular inspection and repair of welding defects can lead to their escalation, potentially resulting in catastrophic failures (Idapalapati et al., 2018). Lack of routine maintenance activities such as cleaning and coating can contribute to corrosion and defect development, with accumulated dirt and debris leading to crevice corrosion at weld joints (Au-Yong et al., 2016). Additionally, relying solely on visual inspections without employing advanced non-destructive testing methods can result in undetected internal defects, emphasizing the importance of utilizing techniques like ultrasonic or radiographic testing for comprehensive defect detection (Tirband et al., 2023). The involvement of key stakeholders in maintenance management is essential for ensuring continuous improvement in maintenance performance and the effectiveness of maintenance strategies (Au-Yong et al., 2017). Predictive maintenance techniques can aid in the early detection and prevention of welding defects, thereby enhancing the overall maintenance efficiency and reducing the likelihood of failures. Furthermore, failure analysis studies underscore the importance of better inspection and maintenance practices for early defect detection and prevention (Idapalapati et. al., 2018). In conclusion, proper maintenance techniques, including regular inspection, cleaning, and the use of advanced testing methods, are essential for identifying and addressing welding defects in a timely manner. By implementing effective maintenance strategies and involving key stakeholders, organizations can mitigate defects, prevent failures, and ensure the integrity and reliability of welded components in various applications. When considering environmental conditions in welding applications, exposure to harsh elements can significantly impact the integrity of welded joints. For instance, facilities located in coastal areas are susceptible to chloride-induced corrosion of welded joints due to the saline atmosphere (Akita et al., 2017). Extreme temperature variations can induce thermal stresses in welded joints, potentially leading to cracks and deformation, especially with repeated heating and cooling cycles causing thermal fatigue and crack initiation. Mechanical stresses during operation, such as pressure fluctuations and vibration, can further exacerbate existing defects or initiate new ones, with pipelines subjected to fluctuating pressures being prone to developing fatigue cracks at welded joints (Yurianto et al., 2020). The impact of environmental conditions on welding processes is evident in the residual stress distribution and mechanical properties of welded joints. Studies have shown that stress states strongly influence the initiation and propagation of stress corrosion cracking and fatigue cracking, emphasizing the importance of considering stress states during operation for assessing structural integrity (Akita et al., 2017). Additionally, the volume expansion and contraction of weld metal during heating and cooling induce local tensile residual stress states, affecting the fatigue strength of cruciform fillet-welded joints (Darcis et al., 2008). Furthermore, the heating and cooling cycles at the end of the welding process can result in permanent residual stresses that remain in the welded joint, highlighting the need to address residual stress effects on weld properties (Yurianto et al., 2020). The distribution of welding residual stress in dissimilar weld joints has been studied to understand the characteristics of residual stress distribution and its implications for joint integrity (An et al., 2022). In conclusion, the environmental conditions surrounding welding operations play a critical role in the formation of defects and the structural integrity of welded joints. Understanding the effects of factors such as temperature variations, mechanical stresses, and exposure to corrosive elements is essential for implementing appropriate measures to mitigate defects and ensure the reliability of welded components.

Conclusion

1. The findings displayed in table 4 above. In 1 show that the heat input (HI) of the welding process is 0. 3 kJ/mm, while cooling rate of the welded joint or CR is equal to 0. basic WAX 490 – 560 ~ Watts and has 36 kJ/mm^2 and shielding gas effectiveness (SGE) is 75%. Assessing the weld quality based on the calculated parameters:

i. High heat input and high rates of cooling are likely to result in conditions, which include; cracking and non-fusion.

ii. Low flow rate pressure of shielding gas also poses a problem of porosity and contamination of the weld pool.

iii. Frequent problems of IAC and welding quality are ISI, incomplete penetration, and undercutting if the welding speed is not enough. With the values got when considering the classifications of welding defects, it can be said that the quality of welding will be good.

1. The findings obtained from model specification in Appendix A- Table A1 depict that prevalence of welding flaws (P) 6.9. The results from, the figures 4.1 to 4.4 Moreover, the results obtained in this research have shown that for liquefied gas distribution facilities the overall prevalence of welding flaws in various components, the values of w1 (Welding Process) should be decreased. Four conditions were given. The flaws in welding

were thus; w2 — the skill level of welders, w3 — the quality of materials and w4 — environmental conditions that were reduced.

2. From these results of Table 4.33reveal that the residual stresses in a welded is 0. It reaches an average true stress of 0117 MPa and the defect deformation rate is 2. 65. A summary of these figures is presented in the figures The above results shows that there is an ascertained causality relation present between the key variables of the study with the use of figures. 5 to 4. 7 have shown that the fundamental reasons behind such welding defects, with regards to material characteristics, welding procedures and environmental conditions is the constants that denote the relative contribution of the shielding gas flow rate factor to defect formation.
3. The idea is the overall quality of the welding process is depicted by β which stands for Coefficient of weld quality. 72, λ: Coefficient of defect severity which indicate the measure of severity of a particular welding defect is 0. 2 and Se (effective structural capacity reduced by the presence of defects) is 20. Because it is possible to estimate the consequences of welding defects in the structures and safety of O&G facilities based on the amount of reduction in structural capacity due to the presence of defects or value of Se, which is low, hence the structural and safety of O&G facilities have been reduced by the presence of defects.

Recommendation

Based on the limitations of this study, the following recommendations for further studies are provided:

1. **Metallurgical and Microstructural Analysis:** Try to employ various metallurgical examinations because they will assist you in defining the grain boundaries, phases and defects in the specific weld at the microstructural level. This can be advantageous in determining the relationship between welding variables and material characteristics in the development of defects, as well as the mechanical characteristics of the welds.
2. **Operational and Maintenance Best Practices:** Carry out research dealing with life cycle practices especially when it comes to the use of welding that would help minimize weld defects. This include preventive and prognostic maintenance methodologies to be employed as well as welders' and maintenance staff education.

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