energies

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Review

Review on Subsea Pipeline Integrity Management: An Operator's Perspective

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Abstract: For operators of oil and gas to save the cost of unforeseen events and risks, and to avoid unnecessary shutdowns, there is a need to have an effective subsea pipeline integrity management system. Currently a large number of subsea pipelines around the globe have already exceeded their design lives; nevertheless, they are still being operated safely, effectively and with diligent consideration towards Environmental, Health and Safety regulations, as well as international standards and best practices. In addition, many older flowlines have no permanent pigging facilities due to various design and operational limitations. For the unpiggable pipeline, the vast majority of the oil and gas operators use different inspection and monitoring techniques to provide essential integrity management data such as product chemistry, cathodic protection, electrical resistance probes and coupons, etc. However, translating such essential integrity management data into meaningful information to make crucial integrity-based decisions can be challenging. This paper presents a holistic approach that implements the required pipeline integrity management tools to facilitate the safe operation and maintenance of pipeline systems going forward. This paper also provides a review of the integrity of the ageing pipelines and underlines the practical pipeline integrity management steps and systems that maintain the condition of the subsea assets going forward.

Keywords: marine hose; subsea pipeline; pipeline integrity management

Citation: Amaechi, C.V.; Hosie, G.; Reda, A. Review on Subsea Pipeline Integrity Management: An Operator Perspective. *Energies* **2023**, *16*, 98. https://doi.org/10.3390/en16010098

Academic Editor: José António Correia

Received: 14 October 2022
Revised: 13 December 2022
Accepted: 19 December 2022
Published: 21 December 2022

1. Introduction

Globally, a significant number of offshore pipeline systems are operated beyond their nominal design lives. With today's state-of-the-art integrity management processes, this is being done in a safe and efficient manner with careful consideration for Environmental, Health and Safety (EHS) regulations, international codes and standards, and operator integrity management standards. In addition, many aging pipeline systems have no permanent pigging facilities, otherwise classified as "unpiggable", which introduces integrity management challenges, particularly for subsea pipelines.

Different operators have presented some challenges of pigging from pipeline integrity management of unpiggable pipelines, dead legs and pipe sections [1,2]. The physical integrity of the pipeline system is typically assessed principally by three methods:

- Inspection (including ILI, monitoring, and surveillance) if the pipeline is piggable.
- Pressure testing (unpiggable pipeline).
- Direct assessment (unpiggable pipeline). Pipelines that cannot be pigged are the most likely candidates for integrity assessment by direct assessment.
- Other integrity assessment methods (i.e., Visual Inspection).

Subsea pipeline integrity is defined by DNV-ST-F101 [3] (as "the ability of the submarine pipeline system to operate safely and withstand the loads imposed during the pipeline life cycle". Other relevant codes and standards describe pipeline integrity and integrity management framework from different perspectives, and indeed pipeline operators around the world have developed their own-pipeline integrity management definitions and practices. In light of that, the Pipeline Integrity Management System (PIMS) is defined as a collection of preventative measures that work together to retain the integrity of the pipeline system.

A number of recent studies on subsea pipelines and risers have addressed guidelines for their integrity management to ensure their safe operation in line with industry best practices [4–6]. For example, Trojette et al. [7] presented an oil operator's integrity approach operating in the UAE, called the Zakum Development Company (ZADCO)'s approach. Due to the gas fields producing past their intended lifespan, the integrity evaluation in ageing exploration and production infrastructures, such as flowlines, collection and gathering systems, is quickly growing to be a source of concern [8,9]. Ragbu et al. [10] conducted an integrity assessment for a gas production pipeline with internal corrosion in a mature field. Rincón and González [11] presented a pipeline life extension using Integrity Management Practices with some case studies.

Pipeline integrity may be severely impacted by the gradual decrease in production flow rate over time which can amplify internal corrosion issues [12–14]. Oxidation, bacterial activity, and localised corrosion, including those cause by deposits, are all factors for concern of pipeline integrity. The challenge in managing the integrity of pipelines, flowlines, and gathering systems, is to accurately predict the rate of internal corrosion, to identify the size, and location of the potential corrosion threat and perform the required assessments to understand the fitness for service (FFS) status. A FFS assessment is a currently methodology used to determine a pipeline's capacity to operate with known defects, and to facilitate any necessary corrective action for maintaining safe pipeline operation while maximising the pipeline's life cycle performance [15–21], however, there are other industry developments and philosophies on subsea pipeline integrity management currently taken into consideration as industry best practice [22–33]. Therefore, there is benefit in presenting an operator's perspective on this subject area which is important in developing industry guidelines.

Oil and gas is a crucial component of global energy demand and will continue to play an important role contributing to rising energy needs globally, as well as facilitating emerging and developing technologies as part of the future energy transition. While fossil fuels continue to have a high demand, the importance of having safe and sustainable operations in the oil and gas industry have never been more important [34–38]. Subsea pipelines, due to their strong track-record and otherwise necessary function in subsea gathering systems, will continue to be relied on heavily to realize energy production from oil and gas reserves. It is because of their importance that there is a need to understand the research state-of-the-art with respect to their integrity management. Where there is a substantial quantity of research published each year, there is a there is a risk that knowledge gaps develop amongst operators, and those companies on which they rely.

The purpose of this paper is to present an operator's perspective on the review of subsea pipeline integrity management systems. This research also presents a holistic approach for implementing the necessary integrity management tools which have been successfully executed to facilitate the safe and sustainable operation and maintenance of the pipelines. The paper also provides a review of mature pipeline integrity management and underlines the practical steps and systems required to maintain the condition of aging assets. This work aims to present a comprehensive understanding of pipeline integrity management, including those which are being operated towards or beyond their original design life, and those that do not include the facilities for performing pigging and typical in-line inspection activities.

2. Industry Guidance on Pipeline Integrity Management

The Pipeline Integrity Management System (PIMS) is intended to highlight the industry practices supplemented by "Industry Best Practice" and thereby assist to certain oil and gas operator to prevent loss of technical integrity, and maximize system availability. The purpose of the PIMS is:

- To promote high standards and continuous improvement.
- To ensure safe and reliable delivery of the products to their customers, without adverse effects on employees, the public, customers, the environment, and incident free operation.
- To ensure that all reasonably practicable steps are taken to prevent loss of technical integrity.
- To establish adequate controls over relevant business activities with the aim of achieving incident-free working conditions.
- To ensure any future legislative compliance.

A Pipeline Integrity Management System (PIMS) is a complex interdependent system that is often difficult to describe, however, in the early development stages it is important to ensure that a sound understanding of industry codes and standards is prioritized. A considerable suite of industry references exists, with the following typically used by most operators:

- ASME B31.8S-2004 Managing System Integrity of Gas Pipelines [39].
- API RP 1160-2019 Managing System Integrity for Hazardous Liquid Pipelines [40].

The requirements detailed in these industry standards with respect to pipeline integrity management are related principally to the following:

- Gathering, reviewing and integrating data.
- Risk assessment.
- Integrity assessment.
- Responses to integrity assessments and mitigation (repair and prevention).

Furthermore, specific and robust integrity management principles which are referenced therein, include:

- The use of comprehensive, systematic, and integrated processes for operation and maintenance.
- Programs shall continuously evolve.
- Programs shall be customised to meet operators' unique conditions.

Pipeline "Industry Best Practice"

This section identifies and references the outline practices, processes, and requirements to be considered to align the PIMS of unpiggable pipelines with industry best practice.

A background to the present-day industry best practices are the processes adopted in the North Sea post-Piper Alpha. That is the introduction of risk management, specifically the onus is on the operator to identify the risks inherent in his pipeline system, and thereafter identify the mitigation measures to reduce those risks "to as low as reasonably practicable". This was a move-away from the previous prescriptive measures imposed on operators through pipeline legislation. As a result, pipeline risk-based legislation was introduced in the U.K.

This approach was quickly adopted within the North Sea in general. At that time (prior to the adoption of this process in the U.S.A.), the implementation of pipeline (risk-based) integrity management in the U.S.A. would have been recommended as industry best practice because there was no legislation nor incorporation within codes of practice. However, this has now been achieved in terms of national legislation and pipeline code of practice through the respective introduction of ASME B31.8S-2004 Managing System

Integrity of Gas Pipelines and API RP 1160-2019 Managing System Integrity for Hazardous Liquid Pipelines [40].

At the same time, incorporation of risk management within other corporate integrated management systems, i.e., internal control or systems to be followed in terms of identification of the stakeholders, management roles and responsibilities, etc., was being achieved. It was therefore recognized that the pipeline industry's best practice follows:

> *Implementation and (ISO, OSHAS, etc.) certification of integrated management systems, in particular the adoption of risk management and subsequent risk-based inspection and maintenance regimes.*

This approach (risk-based integrity management) has been adopted in occidental countries by major oil and gas operators, predominantly as a result of national legislation, and is presently being implemented within regions of pipeline operation on a global basis.

The DNV-ST-F101 [3] standard provides criteria and guidance on concept development, design, construction, operation, and abandonment of Submarine Pipeline Systems. The standard defines subsea pipeline integrity as "the ability of the submarine pipeline system to operate safely and withstand the loads imposed during the pipeline life cycle". The standard is supported by the recommended practice document DNV RP F116 Integrity Management of Submarine Pipeline Systems [41] which states "Pipeline system integrity is defined as the pipeline system's structural/containment function. This is the submarine pipeline system's ability to operate safely and withstand the loads imposed during the pipeline lifecycle. If a system loses this ability, a failure has occurred". Other relevant codes and standards (e.g., ASME B31.8S, API RP 1160), describe pipeline integrity and the integrity management framework in different perspectives, and indeed, many pipeline operators around the world have developed their own pipeline integrity management standards and practices using these comprehensive industry guidance documents.

The primary aim of the PIMS is to ensure the pipeline systems are suitable for the intended purpose and continued service. A secondary function of the system is to aid compliance with any future government regulations governing the pipeline systems.

A Pipeline Integrity Management System (PIMS) seeks to:

- Ensure safe and reliable delivery of the products to their customers, without adverse effects on employees, the public, customers, the environment and incident free operation.
- Ensure that all reasonably practicable steps are taken to prevent loss of technical integrity.
- Establish adequate controls over relevant business activities with the aim of achieving incident-free working conditions.
- Ensure any future legislative compliance.
- Promote high standards and continuous improvement.

Anomalies within the context of PIMS are defects and damage to the pipe that could impact pipeline integrity. Anomalies include, but are not necessarily limited to:

- External corrosion metal loss.
- Internal corrosion metal loss and erosion.
- SCC (Sulphide Corrosion Cracking) colonies.
- Dents.
- Gouges.
- Cracks and crack-like defects (principally in welds).
- Buckles.
- Freespans.
- Sinkage and floatation.
- Corrosion Under Insulation.

The Anomaly Management System defines:

- The roles and responsibilities of the Assessment/Inspection Engineers, the Pipeline Integrity Engineers (including Corrosion Engineers), and Operations in the management, administration, and progressing of anomaly resolution
- How anomaly registers are administered
- How an anomaly's severity is assessed
- How the anomaly is reviewed
- How remediation of the anomaly is undertaken
- How the remediation actions are reviewed
- The reporting and progressing and closing out of activities arising from the resolution of anomalies

Integrity-related actions are required during all stages of the pipeline system life cycle. These stages are:

- Design.
- Construction.
- Commissioning.
- Operation and Maintenance (including modifications).
- Decommissioning.
- Abandonment (Removal/Recovery).

PIMS relies on the interaction between these management systems and their interaction with the Operational and Maintenance activities to maximise pro-active identification of condition degradation and failure modes, thereby assuring integrity of the pipeline system.

During operation a PIMS provides the basis for managing the residual risks and maintenance of the pipeline to provide an efficient operation and verification that the pipeline is fit for continued operation. The PIMS process is not just about the condition of the pipeline and the integrity review it's also about operations. Operations personnel have a key role in maintaining pipeline integrity as a day-to-day operation such as pigging, etc. Integrity review should look at the effectiveness of these activities. If the pipeline systems have not had any formal assessments for a number of years and the condition is unknown, a baseline survey shall be required.

3. Pipeline Integrity Review

As discussed above, this paper focus on mature offshore pipeline networks, often with multiple pipelines in service, and having approached or exceeded their design life. Herein, a Pipeline Integrity Review (PIR) study on mature pipeline network is presented.

The PIR has the following objectives:

- To assess the likelihood and consequences of failure of the offshore pipeline system.
- To identify the level of operational risk related to the offshore pipelines and to detail risk mitigation strategies to ensure that risks are within acceptable industry levels.

These objectives can be achieved by execution of the following key tasks:

- Data gathering, review and integration of the pipeline system data.
- Implementation of a geographic information system (GIS) based Pipeline Integrity Management System (PIMS) software application.
- Evaluation of the condition of the offshore pipeline system, determination of their fitness-for-purpose (FFP) and need for remedial work.
- Determination of the level of risk involved in extending the design life of the offshore pipeline system.
- Identification of the mitigation measures and the costs required to lower the operational risks to an acceptable level in accordance with standard industry practice levels.
- Preparing different study reports for each pipeline (condition, FFP, risk and integrity management plans).

The pipelines should be monitored routinely to track their condition. The following are the principal methods used, but are not necessarily limited to:

- Cathodic protection measurement
- Direct wall thickness measurement
- Route and ROW surveys. For offshore pipelines this includes ROV surveys of pipeline position, length of unsupported spans, and the extent to which pipeline are protected by trenching or burial
- Corrosion Coupons/Probes and Sand Probes
- Product analysis. Analysis includes the following in liquid/gas phases:
    - Water
    - CO_2
    - Dissolved salts
    - Soluble iron
    - Corrosion inhibitor chemicals
    - Methanol
    - PH
    - Chlorides
    - Bacteria

The Pipeline Integrity Reviews (PIR) should be led by corporate single point of accountability for the pipeline with support from the "Pipeline Technical Authority" for the pipeline and its Operations Manager. The pipeline may have many different sections and components for ownership, design, operation and emergency response it is best practice to address and review the pipeline as one system from the source of pressure to the point of discharge.

Incidents affecting pipeline safety, integrity or operation shall be investigated, recorded and be included in any review process. The use certain "world leading" legislation ascertaining to pipeline critical elements (i.e., ESDV's) should be best practice and part of the overall process to ensure these elements have been appropriately identified and that assurance processes are working effectively and the appropriate for the identified risks.

3.1. Task 1: Data Gathering, Review and Data Integration

This initial stage of the PIR may involve site visits to obtain detailed information of the pipeline system(s). PIMS relies on the interaction between the pipeline integrity management systems and the Operational and Maintenance activities to maximise identification of condition status and respective failure modes.

Once the required data for the PIR is collected, data integration may be completed into a PIMS software. Typical data to be collected includes:

- Pipeline alignment sheets.
- Pipeline route data (centerlines) for input into a GIS database.
- Pipeline condition assessment data. Data sets are often by multiple vendors and may include:
    - In-line inspection (ILI) data.
    - Survey data, often by Remotely Operated Vehicle (ROV).
    - Direct examination/NDE (including for unpiggable pipelines).
- Pipeline operating chemistry/composition of production fluids.
- Operational and forecast production rate data.
- Corrosion control data (i.e., CP readings).
- Data relating to platform lifting activities, vessel movements and dropped/dragged anchor related damage was collected and evaluated to generate a bespoke offshore probability model for failure from mechanical damage incidents.

- Information on the detection/isolation/repair times, Emergency shut-down valve (ESDV's), platform populations, the financial losses and the environmental impact associated with small leaks, leaks and rupture releases was collected.
- Additional data elements of pipeline attributes (related to design, operation, maintenance, threats and consequences for use in the risk assessment and FFP) were entered for multiple line segments per pipeline.

The last sub-task within this initial step is to develop a basis of design document for the PIR; the purpose of which was to clearly set out the following:

- The methodologies to be used and the outcome to be obtained.
- The basic data, including assumptions.
- Listing of the software tools to be used.
- Listing of the industry codes and standards to be used.

3.2. Task 2: Establishment of the GIS Based PIMS

At the core of any PIMS is the requirement to effectively manage and to reduce any principal pipeline risks/hazards via the use of data management systems and PIMS software (pipeline condition assessment, risk assessment, integrity management planning and activity management).

The pipeline integrity management system requires a software package, and as a minimum, this software will be able to address all issues in relation to people, integrity process, and any activities required to manage the pipeline system. The selected software should be able to tie the three elements (process, people, and activities) together in a seamless manner. The selected computer PIMS software should be capable of providing the user with a step-by-step workflow through the life cycle of pipeline integrity management.

3.3. Task 3: Engineering Evaluation of the Pipeline Fitness-for-Purpose (FFP)

This task in the PIR project required a thorough engineering evaluation of the design basis and of the condition of the offshore pipeline systems. This evaluation involved the following steps:

- A review of historical and any ongoing inspection, repair, and maintenance activity records (I.e., in-line inspection (ILI), caliper, Automated Ultrasonic Testing (Auto-UT), corrosion and ROV inspections). This process included: Providing feature and significant event summaries for each pipeline based on the available and most recent Auto-UT, ROV, Caliper and ILI surveys, and accounting for any remedial and intervention work conducted since the last survey. This effort ensured that known anomalies, and where they exist, are catalogued as either remediated, or un-remediated anomalies. Utilising this database allowed for the following engineering assessments to be performed:
    - FFP evaluation of the most recently known condition of the pipeline, utilising industry best practice and including.
    - Determination of the current and historical operational parameters.
    - Assessment of the criticality internal and external corrosion based on the feature dimensions as reported by the most recent ILI and/or automated UT inspections.
    - Assessment of the criticality of other reported anomalies, including dents, manufacturing defects and girth weld anomalies, and the assessment of the maximum allowed (critical) span lengths and respective limit state criteria for spanning pipelines.
    - Identification and recommendation of the necessary actions that should be taken to ensure the pipeline is fit-for-purpose based on the known condition.

- Review of external corrosion with the main objective to assess of the pipeline corrosion protection system, including a review of the external survey data of existing Cathodic Protection Systems, and assessment of sacrificial anode depletion. This scope included:
    - Assessment of the current Cathodic Protection (CP) levels based on data from the last CP and anode potential surveys.
    - Comparison of the current potential levels against industry recommended best practices.
    - Summary listing of all anodes including comments on the observed condition.
    - Assessment of the anode depletion rate, determination of the remaining life for each anode and the estimated time to replacement.
    - Prediction of the current anode condition based on the last anode inspection, and extrapolation of the data to determine replacement timelines.
- Review of internal corrosion with the main objective to review the on-going risk from pipeline internal corrosion mechanisms. This included an in-depth operational analysis of the pipelines taking into consideration; product composition, operating conditions (temperature, pressure, flowrate), inhibition, produced water, solids, bacterial contamination, leak history in order to evaluate the internal corrosion threat to each of the pipelines and to estimate deterioration rates.

Based on these described evaluations, the FFP of the pipelines can be established and the required remedial works identified to either maintain safe operating condition moving forward, or to define any remediation required to reestablish a FFP pipeline.

3.4. Task 4: Probabilistic Assessment of Pipeline Failures, Consequence Analysis and Risk Assessment

An estimate is required of the annual failure probability for each line segment and for each of the considered threats. Two approaches for obtaining this estimate have been adopted:

(i) A classical probabilistic approach (load vs. resistance) has been utilised where there is sufficient data available to define probability distributions that describe load and resistance, e.g., this approach is adopted for the Internal Corrosion threat (for the lines with ILI data) and is referred to as an analytical method.

(ii) Where sufficient defect data is not available or the threat does not lend itself to the classical probabilistic approach, the failure probability has been estimated from baseline failure rate estimates which are then adjusted to reflect the impact of pipeline specific attributes (factors which cause or resist the threat), e.g., this approach has been adopted for the Internal Corrosion threat for the lines which do not have ILI data and is referred to as an empirical method.

Both approaches are valid, provide quantitative failure rates and failure probability values, and are commonly used probabilistic methodologies. The latter approach in (ii) can be adopted for ageing pipelines. The approach in (ii) is referred to as an empirical method as it is based on estimating the failure probability from a baseline failure rate that is then adjusted to reflect the impact of pipeline specific attributes (factors which cause or resist the threat). A baseline failure rate estimate for a given threat can be obtained from historical pipeline incident data (either industry published incident data or incident data pertaining to certain operator). These baseline failure rates can be converted to line specific (and segment specific) estimates using modification factors which adjust the baseline failure rate up or down to reflect the specific pipeline conditions. The modification factors are calculated from specific pipeline attributes using algorithms developed from the analysis of historical incident data and expert judgement. The resulting section specific failure rates (per km-year values) can be subsequently converted into corresponding failure probabilities (per year values) by considering the length of the corresponding pipeline or segment of a pipeline.

The threats applicable to the offshore pipelines include:

- Internal Corrosion.
- External Corrosion.
- Mechanical Damage (sub-divided into ship impact to riser, dropped objects and anchor handling threats).
- Sour Cracking.
- Fatigue.
- Weather and Outside Force.
- Equipment Failure.
- Incorrect Operations (upset conditions)

The probability of failure (per year) is determined based on threat per pipeline segment. The pipelines were segmented as follows:

- Start riser.
- Safety zone 1.
- Main subsea section.
- Safety zone 2 (or shore approach).
- End riser.

The consequence of failure values are determined for the following consequence types:

- Health and safety.
- Environmental.
- Financial.

The overall risks are then determined in terms of:

- Health and safety risk.
- Environmental risk.
- Financial risk.
- Overall risk.

The results of the risk assessment can be viewed at the overall pipeline level or drilled down to the individual pipeline dynamic segment level. Results can be viewed in terms of failure probability (overall and by threat), by failure consequence (overall and by consequence type) and by risk (overall and by risk type). Therefore, the number of ways to view and evaluate the results is significant. To facilitate the efficient viewing of results, the PIMS software can automate the production of probability, consequence and risk summary reports where the user can quickly see the key results and easily drill down into the key inputs to identify what is contributing to the results.

3.5. Task 5: Recommendations of the PIR Study

This final output of the PIR is to draw up the necessary documentation and detailed scopes of services for the required rectification and survey works as recommended in the PIR, including:

- Required rectification works.
- Free span Rectifications.
- Pipeline Stabilisation Rectifications.
- Pipeline Crossing Rectifications.
- Sacrificial Anode Retrofits.
- Anomaly repairs.
- Replacement of a damaged pipeline section.
- Installation of pipeline protection.
- ESDV installation.
- ROV, ILI and auto-UT surveys.

4. Conclusions

The proposed PIR can help to identify pipelines that are not fit-for-purpose, or those that garner the highest risks, the then focus on risk mitigation activities to where they are most needed. For oil and gas operators to save cost from unforeseen events and realised risks, and to avoid unnecessary shutdowns, there is the need to have an effective subsea pipeline integrity management system. Currently, a large number of subsea pipelines around the globe have already exceeded their design lives; nevertheless, they are still being operated safely, effectively, and with diligent consideration to Environmental, Health and Safety regulations and international standards and best practices. In addition, most older flow lines have no permanent pigging facilities and are classified as "difficult to pig" due to various design and operational limitations. Most pipeline operators use a variety of inspection and monitoring techniques to provide essential integrity management data such as product chemistry, cathodic protection, ER (Electrical Resistance) probes and coupons, etc. However, translating such data into meaningful information in order to make crucial integrity-based decisions has proven difficult. This paper establishes a holistic approach which implements the required integrity management tools and technology transfer to facilitate the safe operation and maintenance of the pipelines going forward. This review on the integrity of mature pipelines underlines the practical pipeline integrity management steps, presents approaches, tasks and benefits of management systems in order to maintain the condition of these subsea assets going forward.

Author Contributions: Conceptualization, C.V.A., G.H. and A.R.; methodology C.V.A., G.H. and A.R.; software, C.V.A., G.H. and A.R.; validation, C.V.A., G.H. and A.R.; formal analysis, C.V.A., G.H. and A.R.; investigation, C.V.A., G.H. and A.R.; resources, C.V.A., G.H. and A.R.; writing—original draft preparation, C.V.A., G.H. and A.R.; writing—reviewing draft, C.V.A., G.H. and A.R.; data curation, C.V.A., G.H. and A.R.; visualization, C.V.A., G.H. and A.R.; supervision, C.V.A., G.H. and A.R.; project administration, C.V.A., G.H. and A.R.; funding acquisition, C.V.A., G.H. and A.R. All authors have read and agreed to the published version of the manuscript.

Funding: The funding support of the School of Engineering, Lancaster University, UK, and Engineering and Physical Sciences Research Council (EPSRC)'s Doctoral Training Centre (DTC), UK are highly appreciated. In addition, the funding of Overseas Postgraduate Scholarship by Niger Delta Development Commission (NDDC), Port Harcourt, Nigeria, as well as the support of Standards Organisation of Nigeria (SON), Abuja, Nigeria are both appreciated. The financial support received for this doctoral research are highly appreciated.

Data Availability Statement: The raw/processed data required to reproduce these findings are be shared as supplementary data. Though, the data also forms part of an ongoing study.

Acknowledgments: The authors acknowledge the technical support from Lancaster University Engineering Department and Lancaster University Library for the license permission to access the data from the academic databases.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Dutta, R.; Al Suwaidi, I.M. Corrosion management challenges of non-piggable pipelines, sections & dead legs. In Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, United Arab Emirates, 9–12 November 2015. https://doi.org/10.2118/177837-MS.
2. Van Os, M.T.; Achterbosch, G.G.J.; Stallenberg, G.A.J.; Van Mastrigt, P.; Horstink, H.; Dam, A.M. A structural reliability based assessment of non-piggable pipelines. In Proceedings of the CORROSION 2005, Houston, TX, USA, 3–7 April 2005. Available online: https://onepetro.org/NACECORR/proceedings-abstract/CORR05/All-CORR05/NACE-05151/115200.
3. Det Norske Veritas. *DNV-ST-F101*; Offshore Standard: Submarine Pipeline Systems. Det Norske Veritas: Oslo, Norway, 2021.
4. Reda, A.; Rawlinson, A.; Sultan, I.A.; Elgazzar, M.A.; Howard, I.M. Guidelines for safe cable crossing over a pipeline. *Appl. Ocean. Res.* **2020**, *102*, 102284. https://doi.org/10.1016/j.apor.2020.102284.
5. Amaechi, C.V.; Reda, A.; Ja'e, I.A.; Wang, C.; An, C. Guidelines on composite flexible risers: Monitoring techniques and design approaches. *Energies* **2022**, *15*, 4982. https://doi.org/10.3390/en15144982.

6. Amaechi, C.V.; Reda, A.; Kgosiemang, I.M.; Ja'e, I.A.; Oyetunji, A.K.; Olukolajo, M.A.; Igwe, I.B. Guidelines on asset management of offshore facilities for monitoring, sustainable maintenance, and safety practices. *Sensors* **2022**, *22*, 7270. https://doi.org/10.3390/s22197270.
7. Trojette, M.Z.; Al Hammadi, M.; Al Alawi, F. Subsea pipelines integrity management–ZADCO approach. In Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, United Arab Emirates, 10–13 November 2014. https://doi.org/10.2118/171791-MS.
8. Rao, A.R.; Rao, S.S.; Sharma, T.; Krishna, K.R. Asset integrity management in onshore & offshore-enhancing reliability at KGD6. In Proceedings of the SPE Oil and Gas India Conference and Exhibition, Mumbai, India, 28–30 March 2012. https://doi.org/10.2118/153510-MS.
9. Gabetta, G.; Morrea, S.; Travaglia, F.; Cioffi, P.; Monaco, S. Integrity management of pipelines transporting hydrocarbons: An integrated approach. In Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, United Arab Emirates, 9–12 November 2015. https://doi.org/10.2118/177666-MS.
10. Raghu, D.; Pots, B.F.; Amacker, D.; Nguyen, M.H.T. Integrity assessment and management of a gas production line with internal corrosion in a mature field. In Proceedings of the CORROSION 2006, San Diego, CA, USA, 12–16 March 2006. Available online: https://onepetro.org/NACECORR/proceedings-abstract/CORR06/All-CORR06/NACE-06173/118133.
11. Rincón, P.; González, F. Case studies of successful pipeline life extension using integrity management practices. In Proceedings of the CORROSION 2007, Nashville, TN, USA, 11–15 March 2007. Available online: https://onepetro.org/NACECORR/proceedings-abstract/CORR07/All-CORR07/NACE-07141/118490 .
12. Al-Shamari, A.; Al-Sulaiman, S.; Al-Mithin, A.; Jarragh, A.; Prakash, S.S. Corrosion monitoring for Kuwait's pipeline network system. In Proceedings of the SPE Middle East Oil and Gas Show and Conference, Manama, Bahrain, 10–13 March 2013. https://doi.org/10.2118/164190-MS.
13. Marsh, J.; Duncan, P.C. Pipeline internal corrosion assessment, fitness for purpose and future life prediction. In Proceedings of the CORROSION 2010, San Antonio, TX, USA, 14–18 March 2010. Available online: https://onepetro.org/NACECORR/proceedings-abstract/CORR10/All-CORR10/NACE-10053/126707.
14. Okata, S.; Ogbulie, S.U.; George, T. How corrosion management system enhances pipeline integrity in oil and gas exploitation and production company in the Niger Delta of Nigeria Sylvanus Okata and Smart Ogbulie. In Proceedings of the CORROSION 2003, San Diego, CA, USA, 16–20 March 2003. Available online: https://onepetro.org/NACECORR/proceedings-abstract/CORR03/All-CORR03/NACE-03165/114110 .
15. Goodfellow, R. Development of an equipment integrity management system for the long lake Sagd commercial facility. In Proceedings of the CORROSION 2008, New Orleans, LA, USA, 16–20 March 2008. Available online: https://onepetro.org/NACECORR/proceedings-abstract/CORR08/All-CORR08/NACE-08672/119147.
16. Hayes, J. Lessons for effective integrity management from the San Bruno pipeline rupture. *Process. Saf. Prog.* **2015**, *34*, 202–206. https://doi.org/10.1002/prs.11746.
17. Goodfellow, R.; Jonsson, K. Chapter 1: Pipeline integrity management systems (PIMS). In *Oil and Gas Pipelines*; Winston Revie, R., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2015. https://doi.org/10.1002/9781119019213.ch01.
18. Leewis, K.G. Chapter 41: Integrity management of pipeline facilities. In *Oil and Gas Pipelines*; Winston Revie, R., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2015. https://doi.org/10.1002/9781119019213.ch41.
19. CCPS. Chapter 9: Equipment-specific integrity management. In *Guidelines for Mechanical Integrity Systems*; American Institute of Chemical Engineers: New York, NY, USA, 2006. https://doi.org/10.1002/0470048085.ch9.
20. Mora, R.; Hopkins, P.; Cote, E.; Shie, T. Chapter 3: Elements of a pipeline integrity management system (PIMS). In *Pipeline Integrity Management Systems: A Practical Approach*. ASME Press, New York, NY, USA, 2016. https://doi.org/10.1115/1.861110_ch3.
21. Bai, Y.; Bai, Q. *Subsea Pipeline Integrity and Risk Management*, 1st Ed.; Gulf Professional Publishing: Elsevier Publisher Inc., Oxford, UK, 2014. https://doi.org/10.1016/C2011-0-00113-8.
22. Health and Safety Executive. *Guidance on Risk Assessment for Offshore Installations*; Offshore information sheet No. 3/2006; HSE: London, UK, 2006. Available online: https://www.hse.gov.uk/offshore/sheet32006.pdf.
23. Health and Safety Executive. *Guidance of Management of Ageing and Thorough Reviews of Ageing Installations*; Offshore information sheet No. 4/2009; HSE: London, UK, 2009. Available online: http://www.hse.gov.uk/offshore/infosheets/is4-2009.pdf.
24. Health and Safety Executive. *Managing Health and Safety in Construction: Construction (Design and Management) Regulations 2015. Guidance on Regulations. Series L153*; Health and Safety Executive: London, UK, 2015; pp. 1–90. Available online: https://www.hse.gov.uk/pubns/priced/l153.pdf (accessed on).
25. Health and Safety Executive. *Guidance for the Topic Assessment of the Major Accident Hazard Aspects of Safety Cases*; HSE: London, UK, 2006. Available online: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.419.1267&rep=rep1&type=pdf.
26. Oil & Gas UK. *Guidelines on the Management of Ageing and Life Extension of Offshore Structures—Issue 1 April 2012*; Oil & Gas UK (OGUK): London, UK, 2014. Available online: https://oeuk.org.uk/product/guidelines-on-the-management-of-ageing-and-life-extension-of-offshore-structures-issue-1/.
27. Oil & Gas UK. *Guidelines on the Management of Ageing and Life Extension for UKCS Oil and Gas Installations—Issue 1 April 2012*; Oil & Gas UK (OGUK): London, UK, 2012. Available online: https://oeuk.org.uk/wp-content/uploads/2020/09/OGUK-Guidelines-on-the-Management-of-Ageing-and-Life-Extension-for-UKCS-Oil-and-Gas-Installations-Issue-1-1.pdf.

28. Energy Institute. *A Framework for Monitoring the Management of Ageing Effects on Safety Critical Elements*; EI research report, 1st ed.; Energy Institute: London, UK, 2009. Available online: https://publishing.energyinst.org/__data/assets/file/0011/10280/Pages-from-Monitoring-the-management-of-ageing-effects-on-safety-critical-elements-Nov-2009.pdf.
29. Energy Institute. *Performance Standards for Structural Safety Critical Elements*, 1st ed.; Energy Institute: London, UK, 2022. Available online: https://publishing.energyinst.org/topics/asset-integrity/performance-standards-for-structural-safety-critical-elements.
30. Energy Institute. *Guidelines for Management of Safety Critical Elements (SCEs)*, 3rd ed.; Energy Institute: London, UK, 2020. Available online: https://publishing.energyinst.org/__data/assets/file/0012/690789/Pages-from-web-versionGuidelines-for-management-of-safety-critical-elements_LM2.pdf.
31. Energy Institute. *Guidelines for the Management of Safety Critical Elements*, 2nd ed.; Energy Institute: London, UK, 2007. Available online: https://pdfcoffee.com/safety-critical-elements-managament-pdf-free.html.
32. Energy Institute. *Guidelines for the Identification and Management of Environmental Barriers*, 2nd ed.; Energy Institute: London, UK, 2020. Available online: https://publishing.energyinst.org/topics/environment/guidelines-for-the-identification-and-management-of-environmental-barriers.
33. Energy Institute. *Guidelines on the Corrosion Management of Offshore Oil and Gas Production Facilities: Addressing Asset Ageing and Life Extension (ALE)*, 1st ed.; Energy Institute: London, UK, 2017. Available online: https://publishing.energyinst.org/__data/assets/file/0009/305874/Sample-pages-Guidelines-corrosion-management-ALE.pdf.
34. Sundby, T.; Anfinsen, K.A. Development of pipeline regulations in the Norwegian petroleum industry and examples of follow up. In Proceedings of the 2014 10th International Pipeline Conference. Volume 4: Production Pipelines and Flowlines; Project Management; Facilities Integrity Management; Operations and Maintenance; Pipelining in Northern and Offshore Environments; Strain-Based Design; Standards and Regulations, Calgary,Canada, 29 September–3 October 2014. American Society of Mechanical Engineers. https://doi.org/10.1115/IPC2014-33390.
35. Sundby, T.; Anfinsen, K.A. Pipeline regulations in the Norwegian petroleum industry: Experiences, follow-up and statistical summaries of incidents. In Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering. Volume 5A: Pipelines, Risers, and Subsea Systems, Trondheim, Norway, 25–30 June 2017. American Society of Mechanical Engineers. https://doi.org/10.1115/OMAE2017-61234.
36. British Petroleum . *BP Statistical Review of World Energy-2022*, 71st Ed.; BP PLC, London, UK, 2022. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf.
37. International Energy Agency. *World Energy Outlook 2021 (WEO-2021)*; International Energy Agency (IEA), Directorate of Sustainability, Technology and Outlooks: Paris, France, 2021. Available online: https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf.
38. Zhang, K.; Wang, Z.; Chen, G.; Zhang, L.; Yang, Y.; Yao, C.; Wang, J.; Yao, J. Training effective deep reinforcement learning agents for real-time life-cycle production optimization. *J. Pet. Sci. Eng.* **2022**, *208*, 109766.
39. *ASME B31. 8S*; Managing System Integrity of Gas Pipelines. American Society of Mechanical Engineers: New York, NY, USA, 2004
40. *API RP 1160*; Managing System Integrity for Hazardous Liquid Pipelines. American Petroleum Institute: Washington, DC, USA, 2019.
41. Det Norske Veritas. *DNV-RP-F116*; Integrity management of submarine pipeline systems. Det Norske Veritas: Oslo, Norway, 2021.