International Journal of Marine Engineering Innovation and Research, Vol. 11(3), Sept. 2026. 1022-1030
(pISSN: 2541-5972, eISSN: 2548-1479)

Integrated Pipeline Integrity Assessment for Life-Extension Decisions

Panji Anom Prajasutra[1*], Nurhadi Siswantoro[2]

(Received: 3 July 2026 / Revised: 4 July 2026 / Accepted: 10 July 2026 / Available Online: 1 September 2026)

Abstract**—** Oil and gas transmission pipelines operating beyond their original design life require comprehensive integrity assessments to ensure safe, reliable, and sustainable continued operation. Life-extension decisions should not rely only on asset age but must consider actual degradation conditions, operational risks, structural integrity, and remaining service capability. This study proposes an integrated pipeline integrity assessment framework to support technical decision-making for aging transmission pipelines. The proposed framework combines Failure Mechanism Identification (FMI), Risk Assessment (RA), Fitness-for-Service (FFS), and Residual Life Assessment (RLA) into a structured evaluation process. The methodology was applied to a 10-inch API 5L X52 condensate transmission pipeline located in Jambi, Indonesia. Inspection records, ultrasonic thickness measurements, operational data, and engineering evaluation reports were analyzed to determine the actual integrity condition of the pipeline. The results showed that external corrosion was the dominant degradation mechanism affecting the pipeline system. Risk assessment indicated that most evaluated pipeline segments remained within acceptable risk levels. Fitness-for-Service evaluation confirmed that the pipeline satisfied the required acceptance criteria, with sufficient wall thickness for continued operation. Residual Life Assessment demonstrated adequate remaining service capability beyond the original design life. This study confirms that integrated integrity assessment provides a systematic and technically justified approach for supporting risk-based pipeline life-extension decisions.

Keywords— Asset Integrity Management; Fitness-for-Service; Pipeline Integrity; Residual Life Assessment; Risk-Based Inspection.

Corresponding Author: panjiprajasutra@gmail.com

I. INTRODUCTION

Transmission pipelines are crucial to the oil and gas industry. They help move hydrocarbons continuously from production facilities to processing and distribution systems. The integrity of these assets is essential for maintaining operational reliability, environmental protection, public safety, and business continuity. Pipeline failures may result in operational disruptions, significant economic losses, environmental impacts, and safety hazards. Therefore, pipeline integrity management throughout the asset life cycle remains an essential practice to ensure safe and sustainable operation [1], [2].

Many transmission pipelines are still operating even after they were supposed to have been decommissioned. The supposed lifespan is decided when the pipeline is designed. It does not really show how the pipeline is doing after many years. In reality, old pipelines can keep working if we find and manage problems through checks, watching, and fixing. So when we decide to extend a pipeline longer, we should look at how it is really doing, including how much risk it has, how strong it is, and how much longer it can work, not just how old it is. We should not just rely on the years it has been working to decide its fate. Pipeline life extension decisions need to be based on facts about its condition. The condition includes its risk profile, integrity, and remaining service capacity.

Operational capability should be preferred over chronological asset age when making life-extension decisions [3]-[5]. Asset Integrity Management (AIM) provides an organized framework that integrates inspection, monitoring, maintenance, and risk management activities to ensure asset safety and reliability throughout its running life [1]. We need to ensure the pipelines are safe and functioning properly. So companies are using methods to assess pipeline condition and identify risks. This way, they can plan inspections and maintenance in advance. The goal is to keep the pipelines safe and reliable. Many people have researched how to evaluate the integrity of pipelines. They want to find ways to do this. Pipeline integrity is very important. People are working on it.

In recent years, risk-based approaches have played an increasingly important role in pipeline integrity management by supporting more effective inspection planning and maintenance prioritization. Hameed et al. [6] proposed a risk-based inspection methodology that explicitly considers risk exposure when developing pipeline inspection plans. Eskandarzade et al. [7] developed a semi-quantitative Risk-Based Inspection (RBI) approach for pipeline systems, while Wahono et al. [8] highlighted that recent progress in risk-based asset integrity management has expanded RBI implementation via state-of-the-art analytical methods and improved prioritization strategies. These studies underline the importance of risk assessment as a core element of integrity management. However, risk evaluation alone does not yield comprehensive information regarding structural suitability and future operational capability. Additional research has focused on engineering-based assessments and remaining life evaluations of degraded assets. Huang and Shuai [9] developed a pipeline

Panji Anom Prajasutra with Department of Technology Management, Institut Teknologi Sepuluh Nopember, Surabaya, 60264, Indonesia. E-mail: panjiprajasutra@gmail.com
Nurhadi Siswantoro is with Department of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60264, Indonesia. E-mail: nurhadi@its.ac.id

integrity management performance evaluation method that considers multiple integrity-related parameters.

Fitness-for-Service (FFS) methods are commonly used to check if equipment with defects can still be used safely. Zangeneh et al. [10], [11] and Purwidyasari et al. [12] have shown that FFS assessments help evaluate structural problems and guide decisions for older equipment. However, FFS primarily focuses on the current mechanical state and should be combined with risk analysis and predictions of future degradation to develop a complete life-extension plan. Even with recent improvements in pipeline assessment, making good life-extension decisions for aging pipelines remains difficult. Many current strategies rely on separate assessments such as risk analysis, defect checks, or remaining-life estimates, which may not fully capture how different factors interact. This can lead to fragmented decisions, since having some degradation does not always mean a pipeline is unsafe if risk, mechanical integrity, and remaining life are still acceptable. To solve this, a combined assessment method is needed-one that brings together failure mechanism identification, risk evaluation, engineering checks, and remaining-life prediction in a single process.

Few studies have examined how Failure Mechanism Identification and Risk Assessment, Fitness-for-Service, and Residual Life Assessment operate. This research shows that using all of these things together gives us insight into what is going on, which helps us make good decisions about old pipelines. Using Failure Mechanism Identification and Risk Assessment and Fitness-for-Service and Residual Life Assessment is better than using them separately. The main thing this study does is develop a way to assess pipelines that includes identifying what is wrong, quantifying the severity of the problems, checking the structure, and estimating how long they will last. This way, people can make decisions based on the pipeline's condition, not just its age. Asset integrity management also stresses that decisions should consider actual condition, degradation, and risk, not just how long the asset has been in use [2], [13], [14]. The resulting proposed framework offers a structured, technically sound approach to managing risk and making sustainable decisions regarding pipeline life extension. In this study, the framework was applied to assess the condition of a 10-inch API 5L X52 condensate pipeline that had operated beyond its design life. The study was conducted to determine the main cause of the pipeline's deterioration. It also looked at how bad the risks are. The people conducting the study wanted to see whether the pipeline was still usable. They tried to figure out how long it could be used. The study also developed a plan to manage the risks so the pipeline can be used safely for a time. This plan is based on the risks identified. The main goal is to ensure the pipeline can be used safely and in an environmentally friendly way. The pipeline is very important. The study was conducted to help ensure it can be used for a long time without major problems.

II. METHOD

A. Research Object and Data Collection

This research was performed on an operating 10-inch condensate transmission pipeline located in Jambi, Indonesia. The pipeline began operations in 2001 and has now exceeded its initial 20-year design lifetime. The main technical specifications and operating characteristics of the evaluated pipeline system are presented in Table 1.

TABLE 1.
PIPELINE TECHNICAL DATA

Parameter	Value
Pipeline Size	10 inch
Material	API 5L X52
Service Fluid	Condensate
Pipeline Length	17,300 m
Design Pressure	9.30 MPa
Operating Pressure	6.89 MPa
Design Temperature	99.33°C
Operating Temperature	65.55°C
Design Life	20 Years
Installation Year	2001
Latest Inspection	2023
Cathodic Protection	Impressed Current
Coating System	Polyethylene Tape (Buried)

This study used information already available in pipeline integrity documents and historical operational records. The information they collected included details about how the pipeline was designed; inspection reports; results from measuring the pipeline's thickness with ultrasound; data from corrosion monitoring; details about how the pipeline was operated; maintenance records; and reports from past engineering assessments. They used this information to figure out how the pipeline was deteriorating, determine when it was at risk, assess its condition, and estimate how long it could be used. They did all of this based on ideas about managing the integrity of the pipeline assets [1] [2].

B. Research Framework

This study applies an integrated pipeline integrity assessment approach consisting of Failure Mechanism Identification (FMI), Risk Assessment (RA), Fitness-for-Service (FFS), and Residual Life Assessment (RLA). This evaluation framework was developed to comprehensively assess pipeline condition by linking the identification of degradation mechanisms, operational risk levels, structural suitability to operating conditions, and estimation of remaining service life. The integration of these four methods provides a more comprehensive technical basis to support decision-making related to operational safety and pipeline service life extension. The framework was established to furnish a comprehensive assessment of pipeline conditions and to support risk-informed decisions on life-extension feasibility. The integrated methodology follows the principles of Asset Integrity Management and Risk-Based Inspection, as recommended by ISO 55000, API RP 580, API RP 581, and API RP 1160 [1]–[5].

The complete research framework adopted in this study is shown in Figure 1. The framework consolidates degradation-mechanism analysis, risk characterization, structural-strength evaluation, and remaining-life estimation into a single, integrated assessment sequence. The results from each evaluation stage are used to formulate Asset Integrity Management (AIM) recommendations and to provide technical justification for pipeline life-extension decisions.

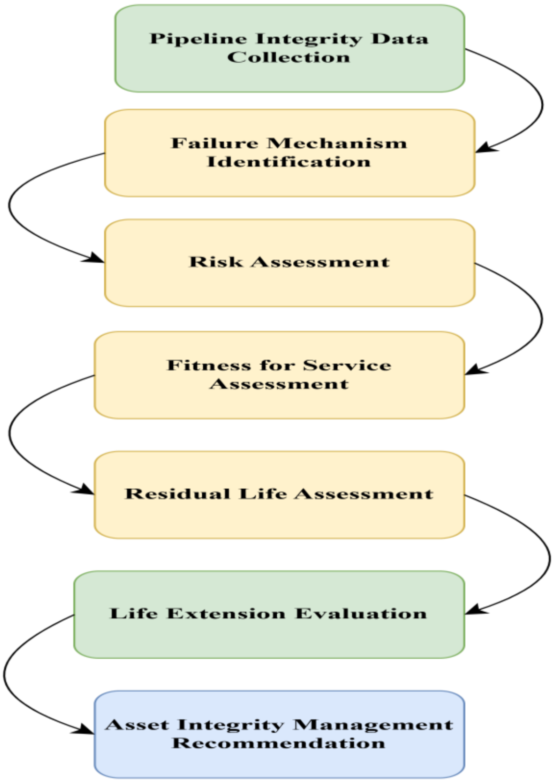

Figure 1. Research Framework

The assessment process begins with Failure Mechanism Identification (FMI) to help identify threats that could impact pipeline integrity. The identified threats are then further analyzed through a Risk Assessment. A Risk Assessment is conducted to determine the likelihood of an event occurring and its consequences. A Fitness for Service (FMS) evaluation is performed to determine whether the pipe is still fit for use. This evaluation helps determine whether the pipe can still perform its intended function safely. Then, a Remaining Life Assessment (RA) is performed to estimate how much longer the pipe can be safely used. The combined results of these assessments are crucial for developing a plan to maintain the pipeline's operational life, based on the FMI, RA, FFS, and RLA, to ensure the pipeline is safe and functioning properly. Manage the pipe's integrity over time and make decisions about it. The plan is based on the results of the FMS, RA, Fitness for Service, and Remaining Life Assessment.

C. Failure Mechanism Identification

Failure Mechanism Identification (FMI) was performed to recognize possible degradation processes that could affect pipeline performance and integrity. The analysis considered several influencing factors, including operating conditions, environmental characteristics, inspection results, corrosion history, material properties, and pipeline design information. The identification process was carried out based on degradation mechanism classifications provided by API RP 571 and supported by established pipeline integrity management approaches [15], [16]. The identified degradation mechanisms were then used as fundamental inputs for the subsequent risk assessment stage.

D. Risk Assessment

Risk Assessment (RA) was carried out using a semiquantitative evaluation method that integrated Probability of Failure (PoF) and Consequence of Failure (CoF). The procedure followed Risk-Based Inspection principles defined in API RP 580 and API RP 581, as well as the risk management framework created by ISO 31000 [3], [4], [17].

The pipeline system was separated into several risk-based segments using a dynamic segmentation method to represent differences in operational characteristics, environmental exposure, and potential consequence severity.

The overall risk value was determined using the following equation:

$$R = PoF \times CoF \tag{1}$$

where R represents the calculated risk level, PoF represents Probability of Failure, and CoF represents Consequence of Failure.

The obtained risk scores were classified into predetermined risk categories and subsequently used to determine inspection priorities and appropriate risk-reduction strategies.

E. Fitness for Service

The Fitness-for-Service assessment is conducted in accordance with API 579-1/ASME FFS-1 for Level 1 assessment. Ultrasonic thickness inspection data is evaluated to determine the remaining pipe wall thickness. A Pipe Suitability Analysis is performed to determine the pipe's suitability for use.

The analysis is carried out by comparing the pipe wall thickness with the thickness required for proper pipe operation. The purpose of the Pipe Suitability Analysis is to ensure that the pipe remains strong enough to function. If a portion of the pipe is thick enough, the pipe is considered safe for continued use in accordance with the provisions of API 579-1/ASME FFS-1 [5], [10], [11].

F. Residual Life Assessment

Residual Life Assessment (RLA) is conducted to estimate the pipe's remaining operational life based on corrosion rate analysis and evaluation of the remaining wall thickness. The assessment procedure referred to the principles established in DNV-RP-F101, the remaining-life prediction methodologies, and the residual-life extension requirements issued by the Indonesian Directorate General of Oil and Gas [12], [17]-[18].

The Residual Life Assessment (RLA) was calculated using the following equation:

$$\text{Remaining Life} = (t\_actual - t\_required) / CR \tag{2}$$

where t_actual represents the actual measured wall thickness (mm), t_required represents the minimum required thickness (mm), and CR represents the corrosion rate (mm/year).

The calculated remaining life values were evaluated against the proposed extension period to determine whether continued pipeline operation remained technically feasible.

G. Asset Integrity Management Recommendation

The results of the Failure Mechanism Identification, Risk Assessment, Fitness-for-Service, and Remaining Life Assessment are integrated to create an Asset Integrity Management plan that helps the pipeline last longer. This plan includes looking at risks to decide when to inspect, being aware of corrosion, measuring the pipe thickness over time, performing maintenance to prevent problems, and regularly re-inspecting the pipeline integrity. The Asset Integrity Management Plan is prepared following the asset management principles as stipulated in ISO 55000 as well as the rules for managing pipeline integrity specified in API RP 1160 [1] [2].

III. Results and Discussion

A. Failure Mechanism Identification

The Failure Mechanism Identification (FMI) evaluation was performed through analyzing inspection documentation, operating history, environmental exposure data, and corrosion monitoring records. Based on the assessment results, external corrosion was identified as a considerable degradation mechanism affecting the integrity of the pipeline system. These results are in line with previous studies, which showed that external corrosion is a major contributor to failure events in buried transmission pipelines, caused by various factors, including damage to the protective coating, soil properties, moisture conditions, and inadequate cathodic protection performance [15], [18], [19]. Therefore, effective external corrosion control remains a critical component for maintaining pipeline integrity throughout the asset life cycle.

Possible degradation mechanisms were also identified during the assessment, including atmospheric corrosion occurring in aboveground facilities, localized internal corrosion influenced by fluid characteristics, under-deposit corrosion, and possible mechanical damage in specific pipeline areas. However, these degradation mechanisms were considered secondary threats when compared with the influence of external corrosion. A summary of the identified degradation mechanisms along with their typical locations within the pipeline system is provided in Table 2.

An organized method foress for identifying possible failure mechanisms is necessary to determine appropriate inspection priorities and maintenance strategies during asset operation. A similar method has been used with Failure Mode and Critical Impact Analysis (FMECA) which provides a step-by-step way to find failure modes, assess their criticality, and assist in risk-based maintenance decision-making, for engineering systems [20]. Although this study applies Failure Mechanism Identification (FMI) rather than FMECA, both methods share the same fundamental objective: methodically identifying degradation processes as a basis for effective implementation of integrity management.

TABLE 2.
FAILURE MECHANISM IDENTIFICATION SUMMARY

Threat Category	Failure Mechanism	Typical Location
Internal Corrosion	General Corrosion	CO_2 containing condensate flow
Internal Corrosion	Localized Corrosion	Low flow area
Internal Corrosion	Under Deposit Corrosion	Sediment accumulation zone
Internal Erosion	Flow Induced Erosion	Low point section
External Corrosion	Atmospheric Corrosion	Aboveground facilities
External Corrosion	Soil Corrosion	Buried pipeline
External Corrosion	Soil-Air Interface Corrosion	Transition zones
External Corrosion	Corrosion Under Support	Pipe support
Mechanical Damage	Third-party Damage	ROW area
Mechanical Damage	Vehicle Loading	Road crossing
Equipment Failure	Valve and Seal Failure	Valve station

The identification of degradation mechanisms provides an important basis for subsequent risk analysis and integrity assessment. Systematic hazard identification is also recognized as an important element in engineering risk management practices. Previous research using the Hazard and Operability (HAZOP) method has confirmed its ability to identify potential operational risks and to support preventive integrity management programs in industrial facilities [21].

A complete understanding of dominant failure mechanisms is required to establish effective inspection methods, maintenance priorities, and integrity management strategies. Based on the degradation threats identified in Table 2, inspection techniques were picked to ensure potential defects throughout the pipeline system could be effectively detected and monitored. Internal degradation mechanisms, including general corrosion, localized corrosion, and under-deposit corrosion, are controlled through ultrasonic thickness measurements, inspections, corrosion monitoring, and periodic integrity evaluation programs.

Meanwhile, external degradation mechanisms such as atmospheric corrosion, soil corrosion, corrosion under support, and soil-to-air interface corrosion are controlled through a periodic integrity inspection and monitoring program. The degradation mechanism control strategy is implemented through inspection of the protective layer, monitoring the performance of the cathodic protection system, and measuring the pipe wall thickness at critical, vulnerable locations. These monitoring activities help detect potential damage early, evaluate the progression of degradation, and ensure the effectiveness of implemented mitigation measures. By implementing a continuous inspection and integrity management program, potential degradation can be controlled, ensuring the pipeline's structural integrity is maintained and enabling safe, reliable operation throughout the service period and extended operational life.

Strategies to minimize risks have been established for the identified degradation categories to maintain long-term pipeline integrity. Recommended mitigation actions for each threat mechanism are summarized in Table 3.

TABLE 3.
THREAT MITIGATION STRATEGY

Threat Category	Recommended Mitigation
Internal Corrosion	Corrosion monitoring and thickness measurement
Under Deposit Corrosion	Pigging and cleaning program
Atmospheric Corrosion	Coating inspection and maintenance
Soil Corrosion	Cathodic protection monitoring
Soil-Air Interface Corrosion	Focused inspection at transition zones
Corrosion Under Support	Support inspection and moisture control
Third-Party Damage	ROW patrol and excavation control
Vehicle Loading	Mechanical protection at crossings
Equipment Failure	Preventive maintenance and testing

The mitigation measures presented in Table 3 form the basis for developing the recommended Asset Integrity Management (AIM) strategy. This integrity management program focuses on corrosion prevention, integrity condition monitoring, maintenance activities, and the control of various degradation mechanisms that could impact pipeline performance. The implementation of this strategy aims to ensure that the pipeline continues to operate safely and reliably in accordance with technical requirements during the service life extension period. Integration between damage mechanism identification, risk-based inspection planning, and implementation of appropriate mitigation measures can make pipeline integrity management more effective at supporting technical decision-making and maintaining the operational sustainability of assets.

B. *Risk Assessment*

The pipeline system was divided into 41 individual segments using a dynamic segmentation approach. This segmentation was conducted to accommodate differences in operating parameters, environmental characteristics, and potential consequence severity along the pipeline route. The dynamic segmentation methodology used in this research is presented in Figure 2 and serves as the basis for examining the distribution of risk throughout the evaluated pipeline system.

Risk evaluation was carried out using the Probability of Failure (PoF) and Consequence of Failure (CoF) approach, in accordance with the Risk-Based Inspection methodology. The generated pipeline risk distribution is illustrated in Figure 3, while the summarized results of the risk assessment are presented in Table 4.

The risk assessment results indicate that approximately 97.6% of the 41 analyzed pipeline segments fall into the Low Risk category, while 2.4% fall into the Medium Risk category; no pipeline segments fall into the High or Very High Risk categories. No pipeline segments were identified within the High Risk or Severe Risk categories. These outcomes show that the pipeline's total integrity condition remains within an acceptable risk range and does not require significant corrective intervention.

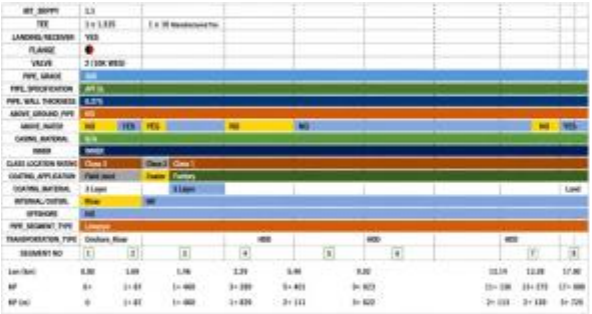

Figure 2. Dynamic Segmentation of Pipeline System

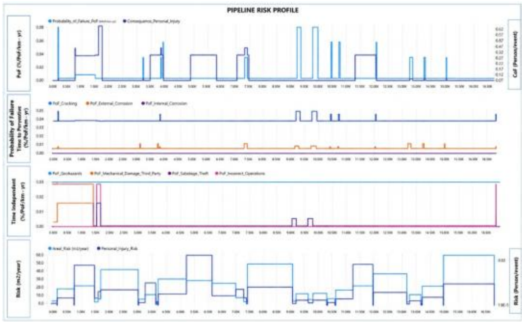

TABLE 4.
RISK ASSESSMENT SUMMARY

Risk Category	Number of Segments	Percentage
Level I (Low Risk)	40	97.6%
Level II (Medium Risk)	1	2.4%
Level III (High Risk)	0	0%
Level IV (Very High Risk)	0	0%

The results obtained correspond to the study by Hameed et al. [6], which reported that Risk-Based Inspection methodologies can successfully identify critical pipeline areas while improving the efficiency of inspection resource assignment. Eskandarzade et al. [7] also demonstrated that semi-quantitative risk assessment provides a reliable approach for prioritizing inspections, optimizing resources, and supporting integrity management. Similar findings were presented by Anggraini and Nurjaya [22], who showed that risk-based assessment methods can support maintenance prioritization and integrity decision-making procedures for aging pipeline assets. Furthermore, Siswantoro et al. [23] demonstrated the successful implementation of Risk-Based Inspection methodology for scrubber vessel assessment in geothermal facilities. The Medium Risk segment identified in this research requires additional monitoring and increased inspection frequency to control the development of future degradation. Nevertheless, the overall risk evaluation confirms that the pipeline system remains acceptable for continued operation.

C. *Fitness-for-Service*

The Fitness-for-Service evaluation was conducted in accordance with API 579-1/ASME FFS-1 Level 1 procedures. This evaluation compared the results of pipe wall thickness measurements with the minimum required thickness criteria and calculated the Maximum Allowable Operating Pressure for Fitness. The results of the Fitness-for-Service evaluation and Residual Life Assessment are summarized in Table 5 below.

The results of the Fitness-for-Service assessment indicate that all inspected pipes are in good condition for use in accordance with API 579-1 and ASME FFS-1. In addition, the pipe wall thickness exceeds the required minimum, and the Maximum Allowable Operating Pressure (MAOP) from the Fitness-for-Service assessment ranges from 19.00 to 19.47 MPa, up from 6.89 MPa. This indicates that the evaluated pipeline maintains sufficient mechanical integrity and pressure-bearing capacity to continue safe operation.

TABLE 5.
FITNESS FOR SERVICE AND RESIDUAL LIFE SUMMARY

Location	Tmin Actual (mm)	Tmin Required (mm)	MAOP (MPa)	Remaining Life	Status
CPS Facility	9.26	4.92	19.47	>20 Years	Accepted
ROW Pipeline	9.14	4.92	19.47	>20 Years	Accepted
Valve Box	>4.92	4.92	>19.00	>20 Years	Accepted

Comparable findings were reported by Zangeneh et al. [10], [11], who concluded that aging equipment can remain suitable for continued operation when the actual wall thickness meets the minimum acceptance requirements and operating parameters remain within the allowable design limitations. The Fitness-for-Service analysis results reinforce the study's core concept that decisions regarding the extension of a pipeline's operational life must be based on an evaluation of the asset's actual condition, technical assessment findings, and structural capability for safe continued operation, rather than solely on the asset's operational age. The results of the Fitness-for-Service evaluation show that all inspected pipes are suitable for continued operation beyond the originally planned period because they remain in good condition and are safe for use.

D. *Residual Life Assessment*

A Residual Life Assessment (RLA) was conducted to estimate the remaining serviceability of the pipeline by taking into account the actual wall thickness and corrosion development during operation. Inspection data from 2016, 2019, and 2023 were evaluated to assess degradation characteristics and predict the pipeline's ability to maintain structural integrity over its extended service life. As shown in Figure 4, the wall thickness probability distribution plot shows a gradual reduction in thickness as the operating period increases. This trend reflects the material degradation behavior associated with the wall-thinning mechanism due to corrosion.

Although wall thickness decreased between inspection periods, the remaining thickness values remained substantially above the minimum required thickness criteria. The corresponding results of the Fitness-for-Service evaluation and Residual Life Assessment are summarized in Table 5.

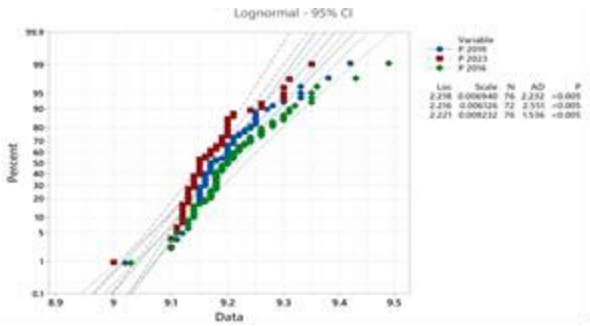

Figure 4. Pipeline Thickness Probability Distribution

The Residual Life Assessment (RLA) results indicate that all analyzed pipeline segments have an estimated remaining service life of more than 20 years. This finding indicates that the pipeline can still maintain the structural integrity and operational capacity required for long-term use, even after exceeding its initial design life. The degradation rate remains within a controlled range, thus not significantly affecting the mechanical strength, reliability, or operational safety of the pipeline during the planned service life extension period. Therefore, the evaluation results indicate that the pipeline is still technically feasible to continue operating based on the actual conditions of the asset.

The findings are consistent with the research by Zhang [13], which demonstrated that remaining-life prediction based on corrosion-rate evaluation and residual wall-thickness calculation provides an effective technical basis for integrity assessment and life-extension decisions. Similar conclusions were also reported by Purwidyasari et al. [12] and Putra et al. [24], who explained that remaining-life assessment can support the safe continued operation of aging assets when combined with Fitness-for-Service evaluation.

These results also support the service life extension evaluation approach implemented by the Directorate General of Oil and Gas of Indonesia, where decisions regarding the sustainability of asset operations place greater emphasis on condition-based assessments rather than on asset replacement that only considers operational life [25]. Overall, the combination of Fitness-for-Service (FFS) and Residual Life Assessment (RLA) evaluations confirmed that the evaluated pipelines still have adequate structural integrity, meet the technical requirements for continued operation, and are worthy of support through the implementation of a planned, integrity-management-based life extension program.

E. *Asset Integrity Management Recommendation*

By combining Failure Mechanism Identification (FMI), Risk Assessment (RA), Fitness-for-Service (FFS), and Residual Life Assessment (RLA), this framework provides a solid technical basis for making decisions about pipeline integrity. The results show that the pipeline can continue operating safely, falls within an acceptable risk range, and has sufficient remaining life to support a ten-year extension, provided integrity management is maintained.

Based on these findings, a risk-based Asset Integrity Management (AIM) strategy was developed to ensure the pipeline stays reliable over time. This strategy follows well-established practices and focuses on risk-based inspections, degradation control, preventive maintenance, and periodic reassessments throughout the pipeline's life [14], [24], [26]. As summarized in Table 6, the proposed Asset Integrity Management (AIM) strategy includes a program of periodic pipe wall thickness measurements, corrosion control and monitoring, risk-based inspection planning, and the establishment of reassessment intervals based on the results of the Residual Life Assessment (RLA). Implementing this Asset Integrity Management (AIM) strategy enables operators to maintain acceptable pipeline integrity through more effective inspection and maintenance management. The strategy also supports optimized resource allocation, controls potential degradation, and ensures the safe and reliable operation of the asset throughout its planned service life extension period. Similar risk-based management methods have also worked well for managing corrosion in other aging assets, demonstrating that combining degradation checks, risk analysis, and maintenance planning can improve long-term reliability [27].

Integration between inspection activities, maintenance strategies, operational monitoring, and engineering assessments is key to the success of an integrity management program. This consolidated approach is an essential component of pipeline integrity assurance and long-term asset reliability, making sure that inspection findings are translated into appropriate maintenance actions and technical decisions throughout the asset life cycle [28]. The proposed Asset Integrity Management (AIM) program consists of periodic risk reassessments, a corrosion monitoring program, pipe wall thickness measurements using the Ultrasonic Thickness Measurement (UTM) method, monitoring the effectiveness of the cathodic protection system, implementing preventive maintenance, and periodic Fitness-for-Service (FFS) evaluations. Implementation of these strategies is necessary to ensure that potential degradation can be identified and effectively controlled, so that the structural integrity, operational reliability, and safety of the pipeline can be maintained throughout the planned service life extension period. These strategies help keep degradation under control and detect potential problems before they become serious.

From an asset management perspective, the framework developed in this study provides a basis for operators and asset owners to make pipeline life extension decisions based on technical evidence, risk profiles, and the actual condition of the asset rather than solely considering its operational age. A condition-based and risk-informed approach allows for more systematic inspection and maintenance decisions, taking into account the priority level of asset integrity. Implementing this strategy supports the optimization of resource allocation, increases the effectiveness of integrity management programs, and minimizes the need for asset replacement before the end of its operational life, as long as the technical evaluation results indicate that the asset still meets the eligibility criteria for continued safe and reliable operation.

TABLE 6.
RECOMMENDED ASSET INTEGRITY MANAGEMENT PROGRAM

Activity	Frequency
Risk Assessment Review	Every 3 Years
Thickness Measurement	Every 3 Years
Corrosion Monitoring	Annually
Cathodic Protection Monitoring	Annually
Fitness for Service Review	Every 5 Years
Residual Life Reassessment	Every 5 Years

Furthermore, this strategy supports operational sustainability by maintaining safety, reliability, environmental protection, and regulatory compliance throughout the service life extension period. The results of this study demonstrate that the application of an integrated framework combining Failure Mechanism Identification (FMI), Risk Assessment (RA), Fitness-for-Service (FFS), and Residual Life Assessment (RLA) can be used as a decision-support approach in managing pipelines that have exceeded their design life. The integration of degradation mechanism identification, risk analysis, structural feasibility evaluation, and remaining service life prediction allows for a more comprehensive assessment of asset condition. Thus, this approach provides a stronger technical basis in supporting Asset Integrity Management strategies and operational life extension decisions based on the actual condition of the asset.

The main takeaway is that aging alone does not mean a pipeline is no longer usable; its condition, risks, and remaining life must be properly assessed. Even though the pipeline studied has been in use longer than planned, the integrated assessment shows it can still operate safely. FMI found external corrosion is the main issue to watch; RA showed that most segments are low risk; FFS confirmed the pipeline is structurally sound; and RLA showed sufficient life remains for the extension. The unique aspect of this framework is its ability to combine diverse assessment results into a single decision-making process. Traditional assessments typically look at everything in isolation. This ensures that all important aspects are considered simultaneously, helping asset managers make risk-based decisions about pipeline life extension. Pipeline life extension is a critical issue for asset managers, so they need to consider all key aspects when making such decisions.

Compared to asset replacement decisions that only refer to the chronological age of the pipeline, the actual condition-based approach provides a more objective basis for operators to determine the priority of inspections, maintenance activities, and mitigation actions based on risk and the condition of the asset integrity. Therefore, implementing this integrated framework can improve the effectiveness of resource allocation, optimize asset utilization, and support the sustainable operation of pipelines that have exceeded their design life, without compromising safety, reliability, or applicable technical requirements.

F. *Research Limitations and Future Research*

This research was performed using historical inspection information obtained from a single operating condensate transmission pipeline located in Indonesia. Therefore, the results of this study may not completely represent other pipeline systems with different material specifications, transported products, operating conditions, environmental characteristics, degradation behaviors, or integrity management strategies. Furthermore, this assessment mainly applied a semi-quantitative risk analysis methodology and deterministic remaining life prediction approach, which may have limitations in representing uncertainties related to corrosion progression and variations in future operating conditions.

Despite these limitations, this study confirms the practical applicability of integrating Failure Mechanism Identification (FMI), Risk Assessment (RA), Fitness-for-Service (FFS), and Residual Life Assessment (RLA) into a comprehensive framework to support pipeline life-extension decision-making. The proposed methodology provides a systematic approach for assessing aging pipeline assets by considering actual degradation conditions, risk exposure, structural reliability, and remaining operational capability.

Future research should expand the implementation of the integrated integrity assessment framework across various piping systems under different operating conditions, environments, and degradation mechanisms to further validate the proposed methodology. Further development can be achieved through the integration of probabilistic reliability analysis, corrosion growth prediction modeling, uncertainty evaluation, and real-time integrity monitoring technology. Furthermore, the implementation of a digital integrity management system supported by predictive analytics is expected to improve the accuracy of degradation predictions and risk evaluations, and the effectiveness of decision-making in pipeline life extension programs, safely and sustainably.

IV. Conclusion

This study developed and implemented an integrated pipeline integrity assessment framework to provide technical support for life-extension decision-making of aging transmission pipeline systems. The recommended framework integrates Failure Mechanism Identification (FMI), Risk Assessment (RA), Fitness-for-Service (FFS), and Residual Life Assessment (RLA) into a comprehensive evaluation process that encompasses degradation mechanisms, risk conditions, structural acceptability, and remaining service capability. The developed methodology follows the principles of asset integrity management and risk-based inspection, which emphasize condition-based evaluation and risk-informed decision-making for managing aging assets [1]–[5], [14], [16].

The application of an integrated integrity assessment methodology to a 10-inch API 5L X52 condensate transmission pipeline in Jambi, Indonesia, demonstrated that pipelines that have exceeded their initial design life can still be objectively evaluated based on the asset's actual condition. The failure mechanism identification results indicate that external corrosion is the primary degradation mechanism that requires control through an integrity management program. The risk evaluation of 41 pipeline segments showed that 40 segments (97.6%) were classified as Low Risk, 1 segment (2.4%) as Medium Risk, and none as High or Very High Risk. These results indicate that the risk level of the entire piping system remains within established acceptable limits, thus supporting continued operational feasibility. This condition can be maintained through a consistent inspection program, integrity monitoring, and risk-based mitigation strategies to ensure that degradation remains controlled during continued operation.

The Fitness-for-Service Evaluation confirmed that all pipeline locations met the acceptance requirements specified by API 579-1/ASME FFS-1 [5]. The calculated Maximum Allowable Operating Pressure (MAOP) values were significantly higher than the operating pressure of 6.89 MPa. This indicates that the pipeline maintains adequate structural strength and pressure-holding capacity. Furthermore, the Remaining Life Assessment results indicated that all pipeline segments have an estimated remaining service life exceeding twenty years. These results indicate that the evaluated pipeline remains technically feasible to operate beyond its original design life under the specified operating conditions.

The results of this study support its primary objective by demonstrating that the recommended integrated assessment framework provides a reliable technical basis for pipeline life-extension decision-making. Furthermore, the results also confirm that decisions regarding asset operational extension should not rely solely on chronological age but should be supported by actual degradation conditions, operational risk levels, structural conditions, and remaining serviceability. Therefore, the proposed methodology provides a practical decision-support system for evaluating aging pipelines and implementing condition-based life-extension strategies.

Based on the overall assessment results, a risk-based Asset Integrity Management strategy is recommended to guarantee the sustainability and effectiveness of the life-extension program. The proposed strategy includes scheduled risk reassessment, ultrasonic thickness inspection, corrosion monitoring, cathodic protection evaluation, Fitness-for-Service review, and periodic Residual Life reassessment. The designed framework can support pipeline operators, asset owners, and regulatory authorities when optimizing inspection programs, focusing on maintenance strategies, ensuring compliance with applicable regulations, and maintaining safe and sustainable operation of aging pipeline assets [14], [25], [29], [30].

Acknowledgements

The authors express their sincere gratitude to Company X for providing access to operational information, inspection data, and technical documentation required to support this research. The authors also acknowledge the contributions and support of the Master of Technology Management Program at Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia, for academic supervision and research facilities during the completion of this study.

The authors also appreciate the contributions of all personnel involved in pipeline integrity evaluation, inspection implementation, and data collection, whose technical assistance was instrumental to the successful completion of this research.

FUNDING INFORMATION

This study did not receive external financial support or specific funding from any organization, including public institutions, commercial entities, or non-profit agencies.

AUTHOR CONTRIBUTIONS

Panji Anom Prajasutra: Conceptualization, Data Curation, Investigation, Formal Analysis, Methodology, and Writing-Original Draft Preparation.

Nurhadi Siswantoro: Supervision, Validation, Methodology Review, and Writing Review and Editing.

CONFLICT OF INTEREST

The authors declare that there are no financial conflicts of interest, competing interests, or personal relationships that could influence the research process, analysis, interpretation, or findings reported in this study.

REFERENCES

[1] International Organization for Standardization, ISO 55000:2014 Asset Management—Overview, Principles and Terminology. Geneva, Switzerland: ISO, 2014.

[2] American Petroleum Institute, API RP 1160: Managing System Integrity for Hazardous Liquid Pipelines. Washington, DC, USA: American Petroleum Institute, 2013.

[3] American Petroleum Institute, API RP 580: Risk-Based Inspection, 3rd ed. Washington, DC, USA: API Publishing, 2016.

[4] American Petroleum Institute, API RP 581: Risk-Based Inspection Technology, 3rd ed. Washington, DC, USA: API Publishing, 2016.

[5] American Petroleum Institute, API 579-1/ASME FFS-1: Fitness-For-Service, 3rd ed. Washington, DC, USA: API Publishing, 2021.

[6] H. Hameed, Y. Bai, and L. Ali, "A risk-based inspection planning methodology for integrity management of subsea oil and gas pipelines," Ships and Offshore Structures, vol. 16, no. 7, pp. 687–699, 2021.

[7] M. Eskandarzade, R. Shahrivar, R. M. C. Ratnayake, and U. N. Bukhari, "An Optimal Approach for Semi-quantitative Risk-Based Inspection of Pipelines," Journal of Pipeline Systems Engineering and Practice, vol. 13, no. 3, pp. 1–13, 2022.

[8] T. Wahono, A. Purniawan, I. Mukhlash, and E. R. M. Putri, "Risk-based asset integrity management in the oil and gas industry from traditional to machine learning approaches: A systematic review," Results in Engineering, vol. 28, Art. no. 107287, 2025, doi: 10.1016/j.rineng.2025.107287.

[9] Z. Huang and J. Shuai, "Performance Evaluation Method of Oil and Gas Pipeline Integrity Management," Journal of Loss Prevention in the Process Industries, vol. 84, Article 105099, 2023.

[10] S. Zangeneh, H. R. Lashgari, and H. R. Sharifi, "Fitness-for-service assessment and failure analysis of AISI 304 demineralized-water pipeline weld crack," Engineering Failure Analysis, vol. 107, Article 104210, 2020.

[11] S. Zangeneh and H. R. Lashgari, "Fitness-for-service assessment of a hydrogen-induced crack in an inlet gas separator pressure vessel using computational modeling," Engineering Failure Analysis, vol. 160, Article 108192, 2024.

[12] S. P. Purwidyasari, A. I. Kurniawan, and D. Ferdian, "Estimating Remaining Life and Fitness-for-Service Evaluation of Fuel Piping Systems," Journal of Materials Exploration and Findings, vol. 2, no. 1, pp. 24–34, 2023.

[13] D. Zhang, "Residual Strength Calculation and Residual Life Prediction of General Corrosion Pipeline," Procedia Engineering, vol. 94, pp. 52–57, 2014.

[14] R. Singh, Pipeline Integrity Handbook: Risk Management and Evaluation. Oxford, UK: Gulf Professional Publishing, 2014.

[15] American Petroleum Institute, API RP 571: Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. Washington, DC, USA: American Petroleum Institute, 2020.

[16] W. K. Muhlbauer, Pipeline Risk Assessment: The Definitive Approach and Its Role in Risk Management. Austin, TX, USA: Expert Publishing LLC, 2015.

[17] International Organization for Standardization, ISO 31000:2018 Risk Management—Guidelines. Geneva, Switzerland: ISO, 2018.

[18] Det Norske Veritas, DNV-RP-F101: Corroded Pipelines Assessment Recommended Practice. Høvik, Norway: DNVGL, 2017.

[19] J. A. Beavers and N. G. Thompson, "External Corrosion of Oil and Natural Gas Pipelines," Corrosion, vol. 62, no. 1, pp. 98–105, 2006.

[20] N. Siswantoro, Semin, and M. B. Zaman, "Criticality Assessment for Marine Diesel Engine Using Failure Mode and Effect Criticality Analysis (FMECA) Approach: Case Study on Lubricating Oil System," International Review of Mechanical Engineering (IREME), vol. 14, no. 4, pp. 258–263, 2020, doi: 10.15866/ireme.v14i4.18060.

[21] N. Cahyono, M. B. Zaman, N. Siswantoro, and D. Priyanta, "Hazard and Operability (HAZOP) Study at Separation System in the Offshore Platform," International Journal on Engineering Applications, vol. 10, no. 1, pp. 41–48, 2022, doi: 10.15866/irea.v10i1.20951.

[22] A. R. Anggraini and D. M. Nurjaya, "Integrity Assessment of Shipping Line Pipelines Using Risk-Based Analysis to Determine Risk and Maintenance Strategies," Journal of Materials Exploration and Findings, vol. 4, no. 1, pp. 28–43, 2025.

[23] N. Siswantoro, D. Priyanta, M. B. Zaman, Semin, P. S. Andaka, and W. Busse, "Risk Analysis of Scrubber Vessel Using Risk-Based Inspection Method in Geothermal Power Plant," IOP Conference Series: Earth and Environmental Science, vol. 649, no. 1, Art. no. 012016, 2021, doi: 10.1088/1755-1315/649/1/012016.

[24] M. B. P. Putra, J. W. Soedarsono, M. Mahendra, Banarwoto, and M. Ghufran, "Remaining Life Assessment and Corrosion Rate on Storage Tank Using ASME/FFS-1 API 579," International Journal of Engineering Trends and Technology, vol. 71, no. 1, pp. 340–348, 2023.

[25] Directorate General of Oil and Gas, Ministry of Energy and Mineral Resources of the Republic of Indonesia, Decree of the Director of Oil and Gas Engineering and Environment No. 183.K/HK.02/DMT/2024: Mechanism for Residual Life Assessment of Installations and Equipment in Oil and Gas Business Activities. Jakarta, Indonesia: Directorate General of Oil and Gas, 2024.

[26] S. A. Miran, Q. Huang, H. Castaneda, and S. Sajedi, "Optimal Inspection Interval Based on Reliability Assessment of Corroded Pipelines," presented at the NACE Corrosion Risk Management Conference, Houston, TX, USA, 2016, Paper No. RISK16-8743.

[27] H. Kurniawan, T. Pitana, and N. Siswantoro, "Risk-Based Integrity Management System of Oil Tanker Hull Structure due to Corrosion," Key Engineering Materials, vol. 940, pp. 121–129, 2023, doi: 10.4028/p-3z2t4s.

[28] M. Mohitpour, H. Golshan, and A. Murray, Pipeline Integrity Assurance. New York, NY, USA: ASME Press, 2007.

[29] P. Hopkins, Practical Guide to Pipeline Integrity Management. Tulsa, OK, USA: PennWell Corporation, 2007.

[30] Directorate General of Oil and Gas, Ministry of Energy and Mineral Resources of the Republic of Indonesia, Technical Guideline for Life Extension of Oil and Gas Transmission Pipelines. Jakarta, Indonesia: Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2024.