Review

A review on pipeline integrity management utilizing in-line inspection data

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ABSTRACT

Pipelines are widely used in transporting large quantities of oil and gas products over long distances due to their safety, efficiency and low cost. Integrity is essential for reliable pipeline operations, for preventing expensive downtime and failures resulting in leaking or spilling oil or gas content to the environment. Pipeline integrity management is a program that manages methods, tools and activities for assessing the health conditions of pipelines and scheduling inspection and maintenance activities to reduce the risks and costs. A pipeline integrity management program mainly consists of three major steps: defect detection and identification, defect growth prediction, and risk-based management. In-line inspections (ILI) are performed periodically using smart pigging tools to detect pipeline defects such as corrosion and cracks. Significant advances are needed to accurately evaluate defects based on ILI data, predict defect growth and optimize integrity activities to prevent pipeline failures, and pipeline integrity management has drawn extensive and growing research interests. This paper provides a comprehensive review on pipeline integrity management based on ILI data. Signal processing methods for defect evaluation for different types of ILI tools are presented. Physics-based models and data-driven methods for predicting defect growth for pipelines with different categories of defects are discussed. And models and methods for risk-based integrity management are reviewed in this paper. Current research challenges and possible future research trends in pipeline integrity management are also discussed.

1. Introduction

Thanks to the advantages of safety, efficiency and low cost, pipelines are widely used in transporting large quantities of oil and gas products over long distances. Pipelines may suffer from different types of defects such as corrosion, fatigue cracks, stress corrosion cracking (SCC), dent, etc. These defects, if not properly managed, may result in pipeline failures including leak or rupture, which could lead to very expensive downtime and environment hazards. There are many pipeline incidents every year around the world, and three of the North America pipelines incidents in 2016 resulted in over 2,000 metric tons of oil and gas leak and spill. Integrity is the top priority for pipeline operators to ensure reliable and safe operations of pipelines, to increase productivity, reduce cost, prevent damage to the environment, support future projects, etc. It is essential to find effective ways to monitor, evaluate and assure the integrity of the pipeline, and reduce the risk of leaks and rupture.

For pipelines, we need to ensure safety, security of supply and compliance with relevant codes and legislation. Procedures and practices are implemented to protect, manage and maintain the integrity of pipeline systems. Due to the significant severity of pipeline failures, the core of pipeline integrity management is to keep pipelines in safe operating conditions. Pipeline integrity tools
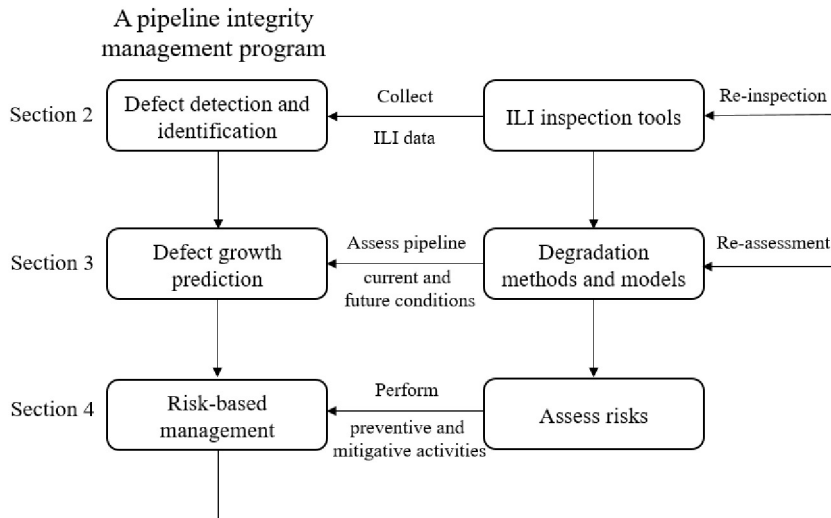

Fig.1. A flowchart for a pipeline integrity management program

are developed to improve business performance, manage risks as well as ensure compliance. Proper pipeline integrity management can reduce both the probability and consequences of failure and increase the pipeline companies' benefits, by properly assessing and managing the defects. Pipeline integrity program monitors and predicts defects and thus adjusts when, where, how, and what actions need to be taken, such as inspection, maintenance and repair. A good pipeline integrity program should be able to manage risk successfully, prevent failure from occurring, control damage effectively, and reduce the overall cost.

A pipeline integrity program generally consists of three major steps:

(1) Defects detection and identification, to obtain defect information through inspection, monitoring, testing and analysis techniques.
(2) Defect growth prediction, to predict defect growth based on damage prediction models and the collected data.
(3) Risk-based management, to recommend optimal inspection, maintenance and repair policies and activities.

Defect information is collected using detection and identification tools. Pipeline companies can gather defect information through walking along the pipelines by technical personnel, hydrostatic testing, in-line inspection (ILI), nondestructive evaluation (NDE), etc. ILI tools are currently the most widely used inspection technology for detecting and inspecting various types of pipeline defects. In this paper, only ILI tools will be discussed and other detection techniques will not be covered. Defect growth prediction is to predict defect growth and when a pipeline failure will occur. There are different kinds of threats to pipeline integrity, such as metal loss, cracking, dents, third party damage, weld, etc. Study on different defect prediction models is the foundation of effective integrity management. The last step, risk-based management, will determine proper inspection intervals, and maintenance and repair actions. The management models will also influence the first step and the second step by possibly changing the inspection actions and defect status. The aim of an integrity program is to achieve accurate defect prediction and balance the reliability and costs in an effective way. Fig.1 shows a flowchart for a pipeline integrity program, and the section numbers in this paper for the three key steps.

Some reported studies considered the design stage as a part of pipeline integrity management process. It is true that pipeline integrity management is a lifecycle approach which involves the design phase, and better design practices typically lead to better pipeline integrity assurance. Study on behaviors of different threats in pipelines as well as inspection and maintenance activities can also give a good feedback to the pipeline design stage. Palmer and King [1] and Antaki [2] provided detailed introductions to the pipeline design stage. Bai and Bai [3] introduced life cycle cost modeling for the design stage of pipeline integrity management. In this paper, though, we will not cover the pipeline integrity design stage, and will focus on detection, prediction and management methods and models during the operation stage.

Pipeline integrity management has drawn extensive and growing research interests, and a large number of studies have been published in conference proceedings and academic journals on methodologies, models and applications. This paper reviews the research studies on pipeline integrity management based on ILI data, with an emphasis on models and methods developed for more effective defect detection, prediction and management. Some published reviews discussed topics related to some subsections of this paper [4–9], with some of them emphasizing failure mechanisms of one type of defect, while some focusing more on applications and practices. Compared with the published reviews, this paper gives more comprehensive and detailed discussions on the methods and models used in the pipeline integrity management framework, and provides an overview on strategies for inspecting, predicting and managing all major pipeline threats. Pipeline integrity management framework and some related case studies were also presented in [10–14]. Legal issues and demands for pipeline integrity programs were discussed in [15]. Pipeline integrity management guidelines are developed by American Petroleum Institute (API) [16], which conducts studies on petroleum industry and provides standards for oil and natural gas industry.

The remainder of the paper is organized as follows. Section 2 describes the ILI tools, which are major technologies to detect and identify the defects, and its performance and applications. Section 3 reviews data-driven and model-based methods for predicting the growth of different types of defects. Section 4 covers methods and models for risk-based management. Conclusions and future research trends are presented in Section 5.

2. Inline inspection tools for defect detection

Due to possible pipeline leakage, environmental damage and high costs of repair and replacement, accurate pipeline monitoring and inspection becomes essential these days. Finding and recording data about pipeline integrity is the first step in pipeline integrity management, and there are a variety of ways to gather information about defects. Varela et al. [17] briefly summarized major methodologies, which are not limited to ILI tools, that are utilized for monitoring and inspecting external corrosion of pipelines and discussed the pros and cons of major inspection tools. For external corrosion as well as other types of threats, there are various inspection techniques to record data on the defects. Pipeline inspection techniques include potential survey techniques, ILI tools, hydrostatic tests, tools for inspecting non-piggable pipelines like pipeline crawlers, etc. These pipeline inspection techniques were briefly introduced in [18,19]. ILI tools will be focused on in this paper.

A high-tech smart pigging device is utilized for in-line inspections, which is inserted in the pipeline and typically pushed through the pipe by the fluid flow from one compressor station to another. Such a smart electronic device is known as a smart pig in pipeline industry. This sophisticated electronic device is essentially a robotic computer that gathers all specific information related to the health condition of the pipeline. The ILI tools can classify the types of defect and their attributes including orientation of defects, size (length, width, depth) and specific location (Internal/External) of the defects [12]. In-line inspection tools can also evaluate pipeline integrity in geohazard areas by mapping techniques [20]. How to get high-quality reports from ILI data was introduced in [21].

Depending on the types of flaws they can detect, ILI tools can be classified as metal loss tools, crack tools, geometry detection tools, etc. Metal loss defects reported from an ILI inspection can be categorized into two main types: pressure based and depth based defects [12]. With depth based defects such as pitting, a pipeline is typically considered failed when the defect depth reaches 80% of the pipe wall thickness in industry, if there are no other specific rules such as NG18, even though sometimes the pipeline doesn't show any failure behavior. For pressure based defects such as corrosion defects, failure is determined by the failure pressure, the model uncertainty and the safety factor [12].

After gathering relevant data through ILI tools, data processing needs to be performed to minimize data errors and extract useful information. There are a variety of signal processing techniques and algorithms for different types of ILI tools. In the following subsections, signal processing technologies and models will also be reviewed for different ILI tools.

2.1. In-line inspection technologies

With the rapid improvement of signal processing technologies, the accuracies of defect profiling, sizing and mapping and ILI tool performance keep improving. And that leads to more cost-effective decisions on pipeline integrity management. A variety of ILI technologies are widely used in the pipeline field, such as Magnetic flux leakages (MFL), Ultrasonic (UT) tools, Electromagnetic acoustic transducers (EMAT), Eddy currents testing (ET), etc. Cartz [22] presented a review of sensor technologies, and Varela et al. [17] discussed ILI technologies that can detect external defects. In the following subsections, main ILI technologies will be reviewed and compared.

2.1.1. Magnetic flux leakages (MFL)

The most widely used tools for in-line inspection of pipeline are MFL tools. This technology can detect different types of defects, such as missing material and mechanical damage, and it is particularly widely used for metal loss inspection in a pipeline integrity management program. MFL inspection tools detect pipeline defects by sensing a local change in a saturating magnetic field, which is generated by huge magnets. The center of the MFL tools is the magnetizer. Gloria et al. [23] presented the development of the magnetic sensor. Ireland and Torres [24] provided a finite element modeling of a circumferential magnetizer under both moving tool and static conditions. The results showed that the magnetic field profile is very complicated and researchers need to pay more attention to studying it in order to further develop MFL tools. Various levels of sensitivity can be chosen based on the testing needs, such as low resolution (standard), high resolution and extra high resolution [22]. The higher the resolution of the MFL tools, the higher the detection capability, which also leads to smaller sensor spacing and higher confidence level of accuracy. But in industry, some companies used standard tools a lot because they believe they are sufficient, faster and cheaper. Kopp and Willems [25] presented a dipole model study of sizing capabilities of MFL tools. As the resolution getting higher, the number of sensors in the system gets bigger. Although it is the most common test and it can meet different testing needs, it may cause the permanent magnetization of pipe after being used and the restriction of the product flow.

Modern, high-resolution MFL inspection tools have the ability to provide very detailed signals. However, most of the MFL data can be easily influenced by various noise sources. To address this problem, many researchers proposed MFL sizing models and analyzed MFL sizing performance. Yeung et al. [26] discussed a technique to improve MFL ILI sizing performance and gave two case studies. Sometimes the sizing performance is more related to the shape of the defects and some sizing algorithms may give bigger sizing error due to the differences of the geometries. To address this problem, Miller and Clouston [27] proposed an MFL sizing model utilizing high-resolution NDE data to give better performance. Signal processing for MFL data is a key element in MFL inspection technique. The primary methods for MFL signal processing are wavelet transform, fast Fourier transform (FFT), Wigner distribution,

etc. Mao et al. [28] gave a brief introduction to MFL signal processing, and they proposed to improve the defect recognition ability though integrating neural network, data fusion and expert system techniques. Saha et al. [29] used wavelet transform to pre-process the raw radial MFL data. Kathirmani et al. [30] proposed a three-stage algorithm for the compression of MFL signals, that is practically feasible and fast. Mean Absolute Deviation, Principal Component Analysis (PCA) and Discrete Wavelet Transform (DWT) were utilized in stage I, II, III respectively. Adaptive algorithms were reported for the processing of MFL signals. Joshi et al. [31] and Afzal and Udpa [32] utilized adaptive wavelets to obtain and process MFL technique signals. Ji et al. [33] employed a fuzzy threshold filter algorithm with adaptive wavelets to process MFL data, and the errors of MFL signals were reduced compared with traditional wavelet transform. Carvalho et al. [34] utilized artificial neural networks (ANNs) to classify MFL signals into signals with defects and signals without defects, and classified the defect signals into external corrosion (EC), internal corrosion (IC), and lack of penetration (LP) with high reliability. Chen et al. [35] presented an empirical mode decomposition (EMD) based method for signal processing of MFL data. Mukherjee et al. [36] proposed a new algorithm of adaptive channel equalization for MFL signal to modify sensor imperfections, which could recover the signal successfully and minimize noises effectively.

2.1.2. Ultrasonic (UT) tools

Currently, ultrasonic is the most reliable in-line inspection technology compared with the other technologies. Ultrasonic inspection generates ultrasonic pulses of high frequency and short wavelength to detect defects or measure pipeline wall thickness. In general, ultrasonic tools give better results and defect accuracy than MFL. The types of flaws UT can detect include internal/external metal loss, cracking, wall thickness variations, etc. They are widely used for detecting stress corrosion cracking and many forms of corrosion. The corrosion penetration depth measurement detection capabilities of UT tools is around ± 0.3 to ± 0.6 mm [37], and for longitudinal and circumferential resolution, it is around 3 mm and 8 mm, respectively. The confidence level is at around 95%, which is more reliable than MFL [38]. As UT crack detection tools require a liquid coupling medium to produce shear waves in the pipe wall, they can be only used for liquid transmission pipelines. As for gas pipelines, EMAT tools can be used instead of UT tools. Lei et al. [39] introduced the ultrasonic in-line inspection pig, which was used for corroded pipelines, and provided the introduction to design stage of the data acquisition system (DAS) as well as the off-line signal processing method. A latest generation of ultrasonic ILI tools was presented in [40], which had high inspection velocity and high resolution, and, as a result, production loss could be avoided and confidence level of inspection results could be improved. In addition, the reported tool generation could deal with higher temperature, higher pressure and bigger speed and wall thickness ranges. UT tools need to be further developed to give more integrity benefits. A brief overview and a case study on ultrasonic phased-array (USCD) technology for the Centennial pipeline stress corrosion cracking were given in [41]. A multilayer data-driven monitoring framework based on signal processing and machine learning techniques was introduced by Ying et al. [42]. Bo et al. [43] gave an introduction to an ultrasonic ILI system for pipelines.

Compared with other tools, UT gives reliable defect depth sizing and good repeatability, and it can deal with very small pipeline wall thickness. Compared with MFL tools, UT tools are also sensitive to a larger variety of features. However, UT tools have the drawback that they require liquid coupling between the pipeline and the transducer (pig), which as a result affects its applications in gas pipelines.

The ultrasonic signals collected by UT tools in pipelines are typically noisy. Effective de-noising techniques are needed to get accurate information regarding defects. The main signal processing methods used for UT signals are wavelet transform [44,45], ANNs [46,47], fast Fourier transform (FFT), etc. Song and Que [44] developed a new technique based on wavelet transform for processing heavily noised ultrasonic signals for the purpose of band-pass filter to get better de-noising results. Martinez et al. [48] employed several digital processing techniques to improve the image quality. Ravanbod [49] employed fuzzy logic and neural networks to improve the algorithm for detecting corrosion defects using ultrasonic testing technique. Ravanbod and Jalali [50] presented an acquisition system for ultrasonic images and proposed a fuzzy edge detection method. Compared with other methods, the proposed method performed better because it has a constant minimum edge contrast. Shakibi et al. [51] developed a signal processing scheme to increase the time resolution of an ultrasonic system. Cau et al. [52,53] preprocessed UT signals with DWT, Blind Separation techniques or FFT to be used as input for neural networks models, to classify the information for defect detection. Chen et al. [54] fused the Morlet wavelet with the least mean squares (LMS) adaptive filter to process ultrasonic signals. Iyer et al. [55] also utilized both wavelet transform and neural networks to process ultrasonic signals. Saniie et al. [56] combined a neural network model with split-spectrum processing for ultrasonic target detection and characterization.

2.1.3. Electromagnetic acoustic transducers (EMAT)

Electromagnetic acoustic transducers (EMAT) are relatively new, and such a sensor consists of a coil at the internal surface of the pipe wall. EMAT generates ultrasound through Lorentz forces without requiring a coupling agent. EMAT is able to detect all kinds of cracks, weld characteristics and wall thickness variations. The mechanism of the EMAT inspection technique was described by Murayama et al. [57]. Salzburger et al. [58] gave a comparison between UT and EMAT and provided a brief introduction to the development of the probe design. Tappert et al. [59] summarized the evolution of the EMAT techniques from 2002 to 2007. EMAT technology is continuously being developed in order to meet harsh environment and higher performance requirements. Kania et al. [60] described the development of EMAT framework and its corresponding validation for SCC crack inspection, and demonstrated that EMAT technology performed very well when identifying and sizing SCC cracks. Hilvert and Beuker [61] gave an introduction to high-resolution EMAT tools for analyzing cracking defects. Hirao and Ogi [62] presented SH-wave EMAT technique for inspecting corrosion defects in gas pipelines.

Since EMAT does not require couplant, which is its biggest advantage, it is readily applicable to gas pipelines and the risk of overlooking defects is reduced. However, EMAT needs to be located less than 1mm from the test body, which is too close to applying

Table 1
Comparison of four main ILI technologies [69]

Tool type	Cracks	Metal loss (corrosion, etc.)	Metallurgical changes	Geometry changes	Others (weld characteristics, etc.)
MFL	N	Y	Y	S	S
UT	Y	Y	N	N	S
EMAT	Y	N	N	N	S
ET	Y	N	S	N	S

Y: The tool can detect this type of flaw.
N: The tool cannot detect this type of flaw.
S: Some types of the tool can detect this type of flaw while others can't.

high frequency. In addition, its detection ability and efficiency are not as good as UT.

Signal processing methods and models reported in the literature for EMAT signals are similar to those for UT signals, since the signals are both ultrasound signals. Tucker et al. [63] performed wavelet analysis to classify the EMAT signals. Mazal et al. [64] compared anti-casual IIR and FIR filters, discrete wavelet transform (DWT) and wavelet packets methods for EMAT signal processing. Through numerical tests, they drew a conclusion that wavelet packet filtering technique performed best among these three de-noising methods. Lee et al. [65] utilized wavelet transform to extract meaningful information from EMAT signals. Kercel et al. [66] utilized wavelet packets and genetic algorithm to process EMAT signals. Bolshakov et al. [67] investigated signal processing methods include frequency filtering (FIR), Gaussian wavelet decomposition, synchronous detection and their combination for analyzing EMAT data.

2.1.4. Eddy current testing (ET)

Eddy current testing is widely used in the automotive, aerospace and manufacturing industries. As an energized coil is brought close to the surface, the impedance of the coil is influenced by the nearness of the induced eddy current. When the eddy currents are affected by the defects, the impedance is also altered, and this change will be measured and used to detect defects. Eddy current testing can only be used on conductive materials. It can detect cracks, and assess wall thickness and laminar defects. It cannot detect external defects because of its limitation of signal through the wall. Detection of SCC using self-excited eddy currents was introduced in [68]. ET does not have any residual effects like MFL, and the test is non-contact. Besides, currents induced by MFL can be detected using ET sensors. However, at current pig speeds, the ILI applications have slow response limits and they are sensitive to coupling variations.

2.1.5. Comparison of the four main ILI technologies

The comparison of four main ILI technologies is as shown in Table 1-1, based on the types of defects they are applicable to. MFL or UT tools are typically used to detect metal loss (external or internal corrosion) in pipelines. When detecting cracks (fatigue cracks and SCC), one uses UT tools or EMAT tools. Besides, a transverse MFL tool is also possible to be used in detecting cracks.

2.2. In-line inspection performance and applications

2.2.1. ILI performance

Understanding the performance of ILI tools is essential for applying them properly. ILI performance is typically characterized by four measures: detection, identification, accuracy, and locating. Detection refers to the capability that a feature is detected by the ILI tool, and the probability of detection (POD) should be usually over 90% for ILI tools. The probability of detection can be defined as:

$$POD = \frac{n_{rep}}{n_{rep} + n_{unrep}}$$

(1)

where n_{rep} is the number of reported features, and n_{unrep} is the number of unreported features. By fitting the POD with different feature sizes, we could obtain POD curve for ILI tool. Different ILI detection tools have different POD curves. We can use a specific function, such as exponential function, to describe the POD curve. The higher feature depth is, the higher POD is. The detection ability of ILI tools has a significant impact on deciding inspection intervals.

Identification indicates the capability to successfully classify and report the type of defects after being detected, and the probability of identification (POI) increases when the size of the defect increases. The incorrect identification and classification of defects will cause significant inaccuracy when predicting the growth of defects. The probability of identification can be defined as:

$$POI = \frac{n_{corr}}{n_{corr} + n_{incorr}}$$

(2)

where n_{corr} is the number of correct identification features, n_{corr} is the number of incorrect identification features. For common features such as corrosion, cracks, we should utilize suitable identification and classification method to ensure POI is beyond 90%.

The sizing accuracy is the most significant measure to assess the performance of ILI tools, and it has a big impact on integrity management of pipelines. The performance of ILI tools can be specified as a tolerance with the corresponding confidence level. For example, the measurement error of the crack depth can be specified as ± 0.5mm at 80% confidence. And it can be easily transferred and represented by the standard deviation of measurement error. And a more accurate ILI tool would produce a more realistic and

less-conservative remaining useful life prediction. Hence, as the accuracy increases, the unnecessary excavations will be reduced, selection of the essential features will be improved and failure pressure will be well predicted. Last but not least, the capability of accurately locating a defect can also affect maintenance and repair activities a lot. The validation of ILI tool performance can be achieved through a hypothesis test following API 1163. ILI tools and technologies are being developed to improve their performance, as a result, it will reduce unnecessary repair actions and/or increase inspection interval for better and more cost-effective pipeline integrity management activities.

To assess and improve in-line inspection performance, algorithms regarding sizing, detection and classification are introduced in the literature. Hrncir et al. [41] gave a case study using a proposed revised sizing algorithms, with which the confidence level of reported feature information was improved. Caleyo et al. [37] presented criteria for assessing the performance of ILI tools. There are three main types of uncertainties in ILI tools which affect performance: systematic error of the ILI tool, measurement noise and random error from the tool and the surface roughness [70]. The effects of combined error on ILI performance were studied in [71,72]. How to deal with uncertainty effects was introduced in [73]. McCann et al. [74] presented a Bayesian method to estimate the ILI performance. Coleman and Miller [75] discussed normalization of data and analyzed tool tolerance and repeatability. Elucidation of the outcomes is a big challenge when comparing multiple ILI inspection datasets in multiple ILI tool runs [75]. Adianto et al. [76] presented the advantages for pipeline integrity program if the ILI tool performs better.

2.2.2. ILI applications

ILI data can be further used to assess and predict the conditions of pipelines, and subsequently plan integrity activities. Examples of analyzing and subsequently predicting pipeline defects (wall loss, cracks, and dents) utilizing ILI data were reported by Anderson and Revelle [77], Alexander [78], Lockey and Young [79] and Ferguson [80]. ILI tools are widely used in the integrity management of corroded pipelines. A comprehensive overview of in-line inspection methods for inspecting corrosion was given in [57]. Potential development directions were also discussed in [81]. Methods for assessing corrosion features, and the application of B31G and RSTRENG criteria for ILI data, were introduced in [82]. Lecchi [83] presented defect assessments of corroded pipelines with the use of ILI tools.

Sizing cracks using ILI tools is also discussed in many papers. Bates et al. [5] presented two case studies on detecting and analyzing cracks through ILI tools. Slaughter et al. [84] described the procedures to analyze the ultrasonic ILI data for cracking and discussed how to improve the crack sizing accuracy. Marr et al. [85] summarized the performance of latest EMAT technology for assessing SCC. Tappert et al. [59] introduced in-line inspection for all kinds of cracks utilizing EMAT based on their operational experience. Hrncir et al. [41] analyzed crack sizing performance of ultrasonic ILI tools. Murayama et al. [86] gave an introduction to the development of the applications of EMAT ILI. Marr et al. [87] described a method to increase the probability of detection and the probability of identification for cracks, and as a result reduce validation costs using EMAT ILI and multiple data sets. Limon-Tapia [88] described a framework for managing crack defects based on ILI tools. Nielsen et al. [89] compared the ILI measurements with field NDE measurements.

Overall, ILI tools have evolved a lot over the past decades in the pipeline industry. Current ILI tools perform relatively reliable in detecting and identifying different types of anomalies. However, the sizing performance of ILI tools needs to be significantly improved to reduce risks and costs. In addition, details of shapes of the corrosion and crack defects need to be captured in the future, which can better assist defect growth prediction and integrity planning. ILI tools also need to be further developed to be suitable for various operating conditions. Signal processing methods need to be further developed within the pipeline industry to remove noise, improve sizing accuracy and provide better performance.

3. Pipeline defect growth prediction

To predict the remaining useful life of pipelines, methods are developed concerning the following three aspects. First, the number of defects. It can be given through ILI tool run, but the probability of detection cannot be 100%. Some methods can be used for updating the true number of defects, such as Bayesian and Nonhomogeneous process. Second, the types of defects. The mechanism for different defects are different, and so it is important to correctly identify each defect. Third, the correlation of defects. For example, a study of crack interaction should be provided for better prediction. Last but not least, the degradation models for different types of defects should be well studied. The determination of remaining useful life of pipeline is based on the degradation models and the sizes of defects, which are detected by ILI tools. And there are a lot of papers in the literature that proposed defect prognostics methods and models.

There are mainly two types of methods for predicting pipeline defect growth, data-driven methods and model-based methods. Data-based methods mainly use ILI data or test data to study the defect propagation stage. Applications of ILI data for defect evaluation are discussed in the previous section, and analyzing defects through ILI data can also give key information for predicting the growth of defects. For data-driven methods, we will mainly discuss pipeline defect growth using ILI data, test data or sample inspection data. Schneider et al. [90] predicted the defect growth and remaining useful life of pipelines using sample inspection data. Examples on the application of ANNs models to predict the failure of oil pipelines were discussed by Senouci et al. [91] and Lu et al. [92]. Remaining useful life prediction for pipelines using support vector machines (SVM) was introduced by Lee et al. [93], and Isa and Rajkumar [94]. Model-based methods mainly apply physical models such as finite element models to perform defect prediction. For example, Liu et al. [95] analyzed the probability of damage of offshore pipelines by utilizing Bayesian networks. Based on the failure probability, pipeline remaining useful life could be predicted using physical models like pipeline degradation models.

The pipeline defect assessment manual (PDAM) is a well-known industry project, which gives best available methods to assess

pipeline defects like corrosion, dents, etc. Cosham and Hopkins [96] provided an introduction to PDAM. Cortese et al. [97] proposed a calibration method for ductile damage estimation of pipelines. A variety of methods and models are available in the literature to predict how a defect grows and when a failure occurs. The methodologies and models used for defect growth prediction depend mainly on the types of defects. Prediction algorithms and models for defects like metal loss, cracking, mechanical damage, and others like third party damage are discussed respectively in the following subsections.

3.1. Metal loss

Metal loss is a major integrity threat to oil and gas pipelines. Serious metal loss can lead to pipeline rupture or collapse. Pipeline metal loss is mainly caused by corrosion and erosion. The prediction methods and models regarding pipelines with corrosion and erosion defects are discussed in this section.

3.1.1. Corrosion

Corrosion is a most common form of defects in pipelines and it can be easily affected by the surrounding environment. Pipeline corrosion is a natural process that happens when pipe materials interact with the working environment, such as soil and water. Corrosion can be divided into two categories, internal and external corrosion. Nine well-known critical environmental factors are soil resistivity, soil moisture, half-cell potential, pH, concentrations of CO_3^{2-}, HCO_3^-, Cl^- and SO_4^{2-}, and distance between the defect and the nearest cathodic protection station [70]. Alamilla et al. [98] developed a mathematical corrosion damage propagation model considering main environmental parameters that influence the propagation of corrosion defects. A large group of pipeline corrosion data from 1922 to 1940 was analyzed in [99]. A corrosion growth model can be further generated by fitting the corrosion damage data.

A pipeline failure caused by corrosion defect can occur when either the failure pressure is smaller than operating pressure, or the depth of defect reaches the critical threshold (normally 80% of wall thickness in industry). The failure stress of a corrosion defect can be expressed as a function of the size and shape of the defect and the geometry of the pipe, as well as the material properties such as yield strength and ultimate tensile strength. The effect of corrosion defect on burst pressure of pipelines is studied in many papers. Netto et al. [100] estimated the burst pressure of pipelines with corrosion defects. The comparison between model predictions with burst tests and long-term hydrostatic tests was presented in [101].

Methods for assessing pipelines with corrosion defects have been extensively studied, and popular code-based deterministic methods in the published literature include ASME B31G [102], modified B31G [103], RSTRENG [103], SHELL92 [104], SAFE [105], DNV-RP-F101 (LPC) [106,107], CPS [108], PCORRC [109–111]. Equations used in these methods are similar and are based on the NG-18 equation [112], except PCORRC. The differences are mainly in the defect shape factor and bulging factor in the NG-18 equation. These methods provide the prediction for corroded pipelines by determining the burst pressure using relevant equations. Defect information such as shape and size and pipeline physical properties such as thickness, diameter and ultimate strength are the main factors that affect the burst pressure. Given the failure criteria, the remaining useful life can be estimated by generating a physics-based model considering the pressure and the defect size versus time. Modified B31G is being verified to be more accurate than B31G, and currently it is the most popular code in the pipeline industry. Cosham et al. [113] presented and compared these various code-based methods used to assess corrosion defects. Caleyo et al. [114] also gave a study and comparison among some of the above-mentioned methods. Some deterministic defect prediction models were presented in the literature. Engelhardt et al. [115] predicted the growth of corrosion damage in pipelines using several deterministic methods. Li et al. [116] studied correlated corrosion defects in pipelines using modified B31G.

Monte Carlo method, first-order reliability method (FORM), and the first order Taylor series expansion of the limit state functions are the main methods that can be combined with deterministic methods for computing the probability of failure for a corrosion defect. In this way, corrosion propagation model is generated and remaining useful life is predicted. Details of these methods can be found in [117]. Larin et al. [118] and Zhang et al. [119] utilized Monte Carlo simulation and 3D FE models to investigate the reliability of pipeline with corrosion defects. Teixeira et al. [120] utilized FORM to assess the failure probability of corroded pipelines and this could be further used to predict the pipeline remaining useful life.

Calculating the corrosion growth rates is an essential part of corroded pipeline integrity management. Corrosion growth models based on corrosion growth rates are also popular in industry. Corrosion rate can be estimated either through the physics-based corrosion models or using ILI data. It was reported in [12] that the latter one gave a better estimate for those pipelines where multiple ILI data sets are available. Race et al. [121] developed a corrosion prediction model for pipelines using ILI data to determine corrosion growth rates. However, there are typically big uncertainties when measuring corrosion growth rates. Spencer et al. [122] compared successive ILI inspections for reducing the bias, when the same ILI vendor is used or different ILI vendors are used. Bayesian method and Markov Chain Monte Carlo (MCMC) simulation have been applied to build corrosion growth models [123–125]. Through combining cluster technique with a Bayesian approach, Wang et al. [70] proposed a methodology to estimate the real external corrosion depth based on ILI inspection and to represent the impact of soil property variation.

Stochastic process models were also reported to assess corrosion defect of pipelines. Using random process corrosion rate, researchers can develop corrosion growth models that lead to a better fit to the data. Bazán and Beck [126] proposed a nonlinear random process corrosion propagation model for pipelines. Zhou [123,127] assessed the reliability of corroding pipelines considering the stochastic process. Valor et al. [128] proposed a stochastic model for modeling pitting corrosion initiation and growth. Alamilla and Sosa [129] gave a stochastic modeling of corrosion propagation based on inspection data.

Other models have also been reported for corrosion growth prediction. Weiguo et al. [130] proposed a method for pipeline

corrosion prediction under cyclic loads. Medjo [131] employed FEM calculations and Complete Gurson Model to determine the corrosion defect development in pipelines. Das et al. [132] assessed turbulence models for predicting flow-induced corrosion defects. Wang et al. [133] used Bayesian inference to propose an integrated method which employed both Monte Carlo techniques and clustered inspection data in order to assess corroded pipelines.

3.1.2. Erosion

Sand particles are often produced along with oil and gas in the pipelines, and they can cause erosion defects when they impact pipeline walls because of change in oil or gas flow direction. The erosive failure of pipeline induced by sand particles is introduced in [134]. A detailed review of sand particle erosion modeling for pipelines was given by Parsi et al. [4], where erosion prediction equations and models were discussed and presented, and further improvements regarding erosion prediction were given.

Erosion prediction models can be categorized into computer fluid dynamics (CFD), experimental and mechanistic models. CFD models were widely used in predicting the erosion damage of pipelines. CFD can be utilized to predict erosion rate and study the impact of different parameters on the erosion rate. CFD tools are accessible, but they are simulation-based and may not be as realistic in some applications. Experimental or empirical methods can be developed by conducting lab tests. They can provide high quality data compared with other methods, but are generally expensive and relatively time-consuming. Mechanistic models such as phenomenological models are analytical ways to predict erosion defects. Although they are fast and inexpensive, the models may be over-simplified and limited in some circumstances. Due to these limitations, researchers proposed a number of erosion prediction models by combining these categories. Ukpai et al. [135] analyzed the impact of sand particle for predicting erosion damage using acoustic emission (AE) technique. Gnanavelu et al. [136] integrated CFD with experimental results to propose a method to predict pipeline erosion. Tang et al. [137] predicted the remaining useful life for a pipe with erosion under multiphase flow condition through CFD modeling techniques. Chen et al. [138] proposed a CFD-DEM coupling method to provide erosion prediction.

3.2. Cracking

Cracking is a critical time-dependent threat to pipelines. There are mainly two types of cracks, namely fatigue cracks and stress-corrosion cracking, which will be focused on in this section. Fatigue crack propagation is defined as the process of weakening pipe material due to pressure variation. Stress corrosion cracking, SCC in short, is the growth of a form of environmental assisted cracks in corroded pipelines. We can divide the crack growth process into three stages. Stage I is the crack initiation stage where the crack growth rate is very small and can be influenced by the environment a lot. Stage II is the stable growth stage. And stage III is the unstable crack growth stage that is less influenced by the environment. Stage III is also called rupture to failure stage, which happens so quickly that it is hard to control. Researchers mainly focus on the first two stages, with an emphasis on stage II. The fatigue life of pipeline can be defined as:

$$N_f = N_i + N_p \tag{3}$$

where N_i is the number of cycles to initiate a crack, and N_p is the number of cycles to propagate to the failure state. We are interested in the remaining useful life, defined by the time between the point when the defect is detected by ILI tools in stage II and the failure time.

The initiation stage of fatigue damage in pipes was studied and explained in details in [139]. Zheng et al. [140] assessed the crack initiation life if pre-deformation exists. Stage II is the stage that researchers mainly focused on. Fatigue assessment can be obtained based on the stress-life method (S-N), the local strain method (Ɛ-N), and Paris' law [6]. The S-N method is an approach based on S-N curve, which can be obtained by fatigue tests. The S-N approach can be employed with algorithms such as Minor's rule, which can be used to accumulate different stress components to further assess the remaining useful life. So the key factors for the S-N method are to determine or select S-N curves accurately, to apply a correction factor and to use a suitable algorithm to combine all the stress contributions. Methods utilized to predict the remaining life of the damaged pipelines based on S-N curves were presented by Pinheiro and Pasqualino [141] and Hong et al. [142]. However, there are some limitations associated with the fatigue S-N approach. It fails to recognize the probabilistic nature of fatigue, and it does not consider the influence of the compressive residual stress resulting from high stress. The Ɛ-N method is another method for fatigue growth assessment, which utilizes ΔƐ-N curves, where N is a function of strain range ΔƐ, and ΔƐ means the total amplitude of strain variations. This method is also similar to S-N approach in some way.

The most popular methods for crack growth models are based on the Paris's law [143]:

$$\frac{da}{dN} = C(\Delta K)^m \tag{4}$$

where $\Delta K = (K_{max} - K_{min})$, with K_{max} being the maximum stress intensity factor (SIF), and K_{min} being the minimum SIF. $\frac{da}{dN}$ is the fatigue crack growth rate, where a is the crack length and N is the number of fatigue cycles. C and m are two material dependent model parameters. These two coefficients can be obtained through either laboratory experiments or industry recommended practices. Reliability analysis for crack defects is more challenging than corrosion defects due to different parameters need to be addressed. There are three primary modes of fracture. Mode I is called opening mode, mode II is sliding mode and mode III is tearing mode. As a result, SIF should also reflect these three modes. Mode I SIF (KI) dominates the magnitude of crack propagation, and many papers only calculate KI to represent the total stress intensity while using Paris' law. In the literature, the majority of physics-based models for predicting cracks in pipelines are based on the Paris' law. To employ the Paris' law, one needs to determine the SIF first. SIF can be

determined through standard codes, numerical equations derived by researchers, experiment results and finite element software (ANSYS, ABAQUS, etc.). There are different equations to calculate the SIF for different crack types. The categories of crack shapes in pipelines are surface, embedded, and through thickness cracks. Shim and Wilkowski [144] applied FE simulation to calculate bulging factor for a pipeline with cracks in the external surface. The bulging factor could be further utilized to determine SIF and crack-driving force. Beside SIF, other measures such as crack tip opening displacement (CTOD) and crack tip opening angle (CTOA) can also be used to determine the fracture toughness of most materials including pipeline materials. Ben Amara et al. [145] gave a study on how to obtain CTOA in steel pipelines.

Popular standards for assessing crack defects include API 579 [146], BS 7910 [147] and NG 18 [112], and many pipeline companies follow these standards to make decisions. Software tools such as CorLAS [148] are also used to analyze these defects. Some other physics-based approaches are also introduced in the literature. These assessment methods require the inputs as follows: crack sizes (length and depth), material properties (Young's modulus, yield and tensile strength), pipeline dimensions (outside diameter, thickness), and loading conditions. The calculation results will then be compared with a suitable safety factor and help to make corresponding decisions. Popelar et al. [149] developed a theoretical model to simulate and calculate the propagation speed of crack in pipelines. Pipeline crack prediction with strain rate dependent damage model (SRDD) through experiments and simulation were investigated by Oikonomidis et al. [150,151], and Yu and Ru [152]. Iranpour and Taheri [153] [154] did research on the impact of compressive stress cycles and peak tensile overload cycles on the fatigue life of pipelines. Amaro et al. [155,156] proposed a hydrogen-assisted fatigue crack propagation model, which is used to predict crack growth using a function of ΔK and hydrogen pressure. Besides, Sekhar [157] summarized the effects as well as the identifications of the multiple cracks, and more studies were needed to consider multiple cracks in pipeline crack growth prediction. Polasik and Jaske [158] described a crack growth model based on the Paris' law and fracture mechanics principles. Hadjoui et al. [159] studied the behavior of crack growth of double butt weld in two pipeline material, X60 and X70. Nonn and Kalwa [160] analyzed multiple published ductile damage mechanics models including Gurson-Tvergaard-Needelman (GTN), Fracture Locus Curve (FLC) and Cohesive Zone (CZ)) for ductile crack propagation in pipelines.

Experimental testing of pipelines with crack defects was performed and reported by many groups. Kumar et al. [161] used acoustic emission (AE) method to study the behavior of crack propagation in low carbon steels which can be used as the pipeline material. Slifka et al. [162] gave tests on two pipeline steel to get fatigue crack growth rate. Jin et al. [163] performed a test on pipeline steel to assess the propagation of a semi-elliptical surface crack. Hosseini et al. [164] compared the experimental testing results they obtained with the industrially known methods, such as BS 7910 and NG 18. Pumpyanskyi et al. [165] performed full scale tests to look into crack propagation and arrest behavior of pipelines. Chen and Jiang [166] gave experimental investigations on crack growth analysis of pipeline material X60. Naniwadekar et al. [167] predicted flaw growth in various orientations based on frequency measurements.

Physics-based models may not be applicable to all situations due to the complexity of the applications and availability of authentic models, and the challenge in determining model parameters. ILI tools are very expensive to run, and sometimes there are not sufficient data to effectively run data-driven methods. As a result, there are great room and challenges for improving prognosis methods and models for cracks in pipelines. Hybrid methods are also being investigated, which integrate physics-based models with data-driven methods. An integrated prognosis method for industrial and mechanical structures was introduced by An et al. [168] using Bayesian inference. Xie et al. [169] proposed an integrated method to predict the remaining useful life of pipelines with fatigue cracks and validated it through field data and simulation examples.

A corrosive environment can affect the growth of fatigue crack [6]. We can call this type of crack environmental cracking or SCC. A probabilistic damage model was proposed by Hu et al. [170] to assess local corrosion crack based on Monte Carlo simulation. Lu et al. [171] presented a high pH stress corrosion crack growth model and validated it through experiment. Imanian and Modarres [172] presented an entropy-based method and did experiments to assess the reliability for corrosion fatigue. Chookah et al. [173] proposed a physics-of-failure model for predicting the propagation of SCC. Jaske and Beavers [174] used the available data and employed J-integral fracture mechanism to predict pipeline remaining life subject to SCC.

3.3. Mechanical damage

Mechanical damage on pipelines also poses threats to pipeline integrity. Two main categories of mechanical damage are dents and gouges. Bai and Bai [175] gave an introduction to dented pipes including limit-state based criteria, fracture mechanism and reliability-based assessment. A mechanical damage integrity management framework was given in [11]. The burst pressure for pipelines with gouges and dents was studied by Lancaster and Palmer [176], Allouti et al. [177] and Ghaednia et al. [178]. Pressure strength of pipelines with dents and cracks were studied in [179]. Macdonald and Cosham [180] discussed the pipeline defect assessment manual (PDAM) and suggested practices for dents and gouges assessment as well as the limitations of these assessment methods. Cosham and Hopkins [181] analyzed the dents effect in pipelines based on PDAM.

Prognosis algorithms and models are proposed for mechanical damage in pipelines. Ivanov et al. [182] proposed an FE model using MFL signals to predict the growth of mechanical damage in pipelines. Bolton et al. [183] proposed a finite element model for predicting the life for dented pipeline and validated the model by experiment. Dama et al. [184] used a simple S-N approach to assess the structural condition of pipelines with sharp dents. Bolton et al. [185] developed a finite element model for dented pipes to estimate the remaining life. Azadeh and Taheri [186] performed an experimental investigation on dented pipes. Failure prediction of the pipeline with dents based on local strain criteria was studied by Allouti et al. [177] and Noronha et al. [187].

3.4. Other defects

Other types of defects, such as weld, third party damage, etc., can cause the failure of pipelines. The main differences between corrosion, cracking and the other failure mechanisms (third-party damage, laminations and earth movements) are the nature of mechanism and failure rate tendency. The nature of mechanisms of corrosion and cracking are time-dependent while the others are generally random, or time-independent. The failure tendencies for corrosion and cracking increase with time, while those for the others remain constant. To better control third party damage, regular surveys of the line, good communications, and good protective measures are important. Goodfellow et al. [188] presented the updated distributions of third party damage with the use of historical data. Hsu et al. [189] provided an introduction to weld mechanism and introduced wear prediction models for metals. El-Hussein [190] compared the FE predictions for third party attacks with real field data. Oddy and McDill [191] employed 3D FE analysis of welding on pipelines to perform predictions. Niu et al. [192] applied FE simulation to give a creep damage prediction of pipelines in the high temperature and high pressure environment.

4. Risk-based management

The common definition of risk is the multiplication of probability and consequence. Thus, to perform risk-based management, we need to analyze the causes of risks, estimate failure probabilities as well as perform consequence analysis. For pipeline integrity management, probabilities typically refer to probabilities of pipeline failure due to certain defect growth. The consequences are related to the costs incurred by activities like inspection and maintenance, loss of productivity, rehabilitation and investigation, damage to the environment and community, environmental cleaning up, etc.

While conducting risk-based management for pipelines, some related areas need to be studied. First, threats and consequence need to be identified in order for calculating risk. Selecting a proper risk assessment model is critical to determine the structural integrity. Second, pipeline segments and existing threats must be prioritized. In this way, the riskiest pipeline segments and threats will be inspected and repaired prior to others. Third, select suitable mitigation and preventative activities for each threat. Last but not least, determine cost-effective and appropriate re-inspection and re-assessment interval. This re-assessment interval must ensure the safe operation of pipelines and the reliability of pipelines should be beyond the predetermined safety threshold.

4.1. Activities for RBM

To evaluate the life cycle cost of pipeline risk-based management, potential activities need to be well discussed and studied. Activities for risk mitigation include visual inspection, potential surveys, cathodic-protection inspection, in-line inspection, operational pigging and other maintenance and repair activities. Emergency plans for failure and accidents also need to be considered. The principal objective of risk-based management activities is to efficiently and effectively utilize available resources to ensure the safety of public, surrounding environment protection and pipeline system reliability. The frequency of inspection and maintenance activities depends not only on the defect damage situation and the consequences of failure, but also on the pipeline operating conditions. Besides, risk acceptance criteria need to be determined before risk-based management process, based on industry regulations and codes, operators as well as risk analysis outcomes. Pipeline risk analysis for integrity management was introduced in [193–196]. The advantages and disadvantages of pipeline risk analysis were discussed by Bott and Sporns [197].

Inspection activities are well discussed in Section 2. The unit inspection cost of ILI tool increases as tool accuracy increases. With the consideration of time effect (discount rate), the reassessment interval will make a big impact on inspection cost calculation. Besides, sizing uncertainty is non-negligible while conducting cost evaluation. After the inspection activities, types of defects and their significance to pipeline integrity should be studied. The findings from inspections and tests need to be basically aligned with what the prognostics model predicted. If not, the reasons for that need to be investigated. Besides, the causes of these defects need to be investigated for future preventive and mitigate actions.

As for repair activities, repair criterions and methods are well discussed in [16,198]. For each kind of defect, certain repair criteria can be utilized to determine the corresponding repair actions. Repair methods for pipeline include pipe replacement, recoating, full-encirclement sleeves, composite wrap repairs, mechanical clamps, etc. Repair criteria can be determined based on the severity of ILI indications. There are four types of responses to pipeline inline inspections: immediate, near term, scheduled and monitored. For each one, there are time and limit state requirements for repair actions, which can be found in [16]. The costs for repair activities depend on the type of repair methods and the number of defects needs to be repaired. The locations of defects and pipeline segments also affect the repair or replacement costs. Industry does want pipelines to fail that causes damage to population and environment. Therefore, predictive and preventive maintenance activities are better choices than reactive maintenance activities. The most suitable maintenance activities should be arranged based on the probability of failure of pipelines.

4.2. Methods for RBM

Risk assessment methods can be divided into three types: quantitative methods, qualitative methods and semi-quantitative methods. Quantitative methods require lots of input data which may include some data that the pipeline operators do not have. If the input data is enough, the output will provide very detailed mitigation and inspection options and criterions. These methods are not efficient or cost-effective for upstream pipelines. Qualitative methods are simple decision matrix methods. These types of methods depend on experts and industry practices a lot. These methods are very effective for ranking pipeline risk. However, they are

relatively more conservative and they do not provide optimized schedule and actions for mitigation and inspection activities. Semi-quantitative methods can also be called score index methods. These methods are widely used in industry. The required input data are relatively less than quantitative methods and easy to acquire. Relative risk values and optimized solutions for mitigation problems will provide as the output of these methods.

Analyzing the reliability and risks is the essential job in the preparation stage for risk-based management. Risk can be obtained by calculating the probability of failure and consequence of failure. Many papers discussed the inputs for the risk-based management. Chien and Chen [199] carried out the reliability assessment of pipelines to provide the integrity management strategies, and the reliability analysis method they used was first order second moment (FOSM) method. Kuznetsov et al. [200] implemented Bayesian method to count the number of defects in a pipeline segment, and it can be further utilized in determining the inspection and maintenance activities. Cunha [201] compared and analyzed the failure statistics for pipelines which can also be further utilized as the basis for risk-based management. McCallum et al. [202] developed a corrosion risk management tool using Markov analysis, which can assist corrosion integrity planning. Mihell and Rout [203] proposed an approach to analyze risk and reliability for pipelines. Tuft et al. [204] provided the comparison between reliability-based analysis method and quantitative risk assessment based on historical failure rates.

There are two main objectives in risk-based management models. One objective is to minimize the whole life cycle cost with the constraints of certain reliability and risk level, and the other objective is to minimize the risk. Risk-based management following the first objective has three main steps. First, define and gather information on threats and defects in the pipelines. Second, calculate probability, consequence of failure and life cycle costs. Third, recommend inspection and maintenance activities by solving the optimization problem to minimize total costs while ensuring the system reliability is above a certain level. Various approaches and models were reported with cost minimization as the main objective. Dawotola et al. [205] proposed a method where the failure rate changes with time following a nonhomogeneous Poisson process. The historical data were fitted to obtain the probability of failure, and maintenance strategies were optimized by minimizing operation and maintenance loss while meeting risk and reliability target. Bai et al. [206] proposed a tree risk-based inspection approach for subsea pipelines to minimize cost for different safety levels. Sinha and McKim [207] utilized Markovian prediction models to construct a cost-effectiveness based prioritization program to develop strategies for maintenance and repair. Life cycle cost optimization was performed using Genetic Algorithm (GA) for pipeline networks by Tee et al. [208]. In addition, inspection, maintenance and repair strategies for different types of defects in pipelines were also reported. Sahraoui et al. [209] provided a review of risk-based management methods that considered the uncertainties in the inspection results for pipelines with corrosion defects. Stephens et al. [210] studied reliability corrosion assessment to develop cost-effective maintenance and inspection planning strategies, and they adopted a random process model to generate new defects when calculating the probability of failure. Hong [211] developed inspection and maintenance schedules based on reliability constraint for corroded pipelines. Moreno et al. [212] extended the inspection interval using a statistically active corrosion (SAC) method. Xie and Tian [213] proposed a method to determine optimal re-inspection and re-assessment interval for pipelines with corrosion defects based on PoF threshold as a random variable. Gomes et al. [214] optimized the inspection planning and repair intervals for pipelines with external corrosion defects. Gomes and Beck [215] also optimized pipeline management subject to random cracks. The number of inspections and critical crack size were considered as design variables in the models.

The second optimization objective used in many studies is risk minimization, mainly aiming to reduce the likelihood (probability of failure) and/or the consequence (severity). These kinds of methods follow three steps. First, define a risk and the acceptance criteria. Second, assess the risk and determine the risk level. Third, establish inspection, maintenance and assessment plans based on risk assessment results. Some papers in the literature proposed methods following the process above. Kamsu-Foguem [216] presented an introduction to risk-based inspection management, and suggested a methodology based on a colored risk matrix for providing risk acceptance criteria. Tien et al. [217] proposed a method to determine the optimal pigging inspections planning, with information like damage factor, inspection factor, condition factor, process factor, etc., collected and qualified to form the model built in this paper. Khan et al. [13] proposed a method for risk-based inspection and maintenance modeling using gamma distribution and Bayesian method to describe material degradation process. Kallen and van Noortwijk [218] proposed an adaptive Bayesian model for optimal integrity planning, which used gamma stochastic process to describe the degradation mechanism.

Many studies on maintenance planning were reported for pipelines with a specific defect type, particularly corrosion defect. Singh and Markeset [219] proposed a method to estimate corrosion growth rate for pipelines based on fuzzy logic method. A decision support system (DSS) was utilized for assessing risk effects and developing pipeline integrity plans in [220] and [221]. Condition-based maintenance models developed for multi-component systems were introduced in [222,223]. Seo et al. [224] discussed the development and application of the proposed risk-based inspection method for pipelines with corrosion defects. Fessler and Rapp [225] proposed a method for determining the reassessment intervals for pipelines with SCC defects. Zarea et al. [9] gave an introduction to risk management along with integrity management of mechanical damage in pipelines.

5. Conclusions

Integrity has been the top priority for the pipeline industry, and plays a critical role for the oil and gas industry as a whole. Significant advances are needed in pipeline integrity management to develop more effective methods, models and technologies to accurately monitor and predict pipeline conditions, extend the lifetimes of pipelines and prevent potential ruptures and the resulting consequences. In this paper, three main steps of a pipeline integrity program have been discussed. Key ILI techniques along with their performance and applications have been reviewed. Data-driven methods and physics-based model for predicting pipeline defect growth have been discussed in details. Risk-based inspection and maintenance methods and models have also been presented. In-line

inspection, defect prediction and risk-based planning, which are three main steps of pipeline integrity management, actually form a closed loop. Plan, schedule, execute, analyze and improve are the elements of the loop of the activities need to be performed to manage pipeline integrity.

In conclusion, the main objectives of pipeline integrity management are listed as follows:

(1) Identify and assess all reasonable expected defects and threats to safety in the design, construction and operation of pipelines.
(2) Ensure the safety of the population, prevent failures that could cause damages to the surrounding environment.
(3) Allocate available resources to pipeline integrity activities such as inspection and maintenance as efficient and effective as possible.
(4) Reduce high costs, high risks and unnecessary shutdown while ensuring the system reliability reaches suitable level and complying with regulatory codes.

In addition to the research studies reviewed in this paper, fundamentals of pipeline integrity management were covered in several books. Mohitpour [69], Singh [226], and Revie [227] provided introductions to basic concepts and assessment actions to assure pipeline integrity. Timashev and Bushinskaya [228] presented an introduction to prognosis and reliability of pipeline systems, where ILI results analysis, reliability analysis and methods for assessing pipeline system were covered. Muhlbauer [221,229] introduced methods for managing pipeline risks. Bai [230] presented an introduction to risk management of different categories of threats in pipelines. ILI technologies and applications were discussed in [231]. The regulations of pipeline safety were presented for Great Britain in [232].

Today still about half of pipelines are non-piggable, where smart pigs and ILI cannot be employed, and challenges exist when gathering valuable data utilizing direct assessment methods for defect growth prediction. As to piggable pipelines, although ILI technologies are continuously being improved at a fast pace, the measurement errors of ILI tools can still cause large uncertainties when evaluating defects and predicting defect growth. Each individual pipeline has its specific situations, and it's hard to develop physics-based models that consider all these specific factors. In this case, both data-driven methods and physics-based models for pipeline defect growth prediction may not be accurate enough and may lead to poorly managed integrity activities. Multiple ILI tool runs can give more accurate results but cost more. Many reported approaches and models in the literature were not thoroughly validated. More effective communications are needed between researchers and the industry.

To address these problems, the following research directions need to be further investigated in pipeline integrity management. In-line inspection sensor technologies and pipeline integrity practices must continue to evolve. Other inspection technologies need to improve too for non-piggable pipelines. More reliable and effective signal processing and data analysis methods need to be developed for noise removal in ILI data and accurate defect evaluation. Prognostics approaches and models need to be further improved. Minor repair and imperfect repair actions need to be considered and compared with other maintenance actions. Balancing the ILI tool run times with costs also need to be further investigated. Different pipeline integrity management frameworks need to be further developed regarding different types of defects. Effective validation methods and technologies also need to be established.

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