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# Failure probability calculation model applied to gas pipelines

Frederico C. M. Thom[1], Geraldo R. Sisquini[2], Matheus J. de Jesus[3], Oldrich J. Romero[4]

[1]*SUPRIMENTOS/GCB/GQ, Petrobras*
*Vitória - Espírito Santo - Brasil*
*thom_vix@yahoo.com.br*
[2]*Departamento de Engenharia Mecânica, Universidade Federal do Espírito Santo – UFES*
*Vitória - Espírito Santo - Brasil*
*geraldo.sisquini@ufes.br*
[3]*Tecnologia da Informação, Multas Brasil (MBR)*
*Vitória - Espírito Santo - Brasil*
*matheus.jhordao@gmail.com*
[4]*Departamento de Engenharia e Tecnologia, Universidade Federal do Espírito Santo – UFES*
*São Mateus - Espírito Santo - Brasil*
*oldrich.romero@ufes.br*

**Abstract.** This article presents an application for failure probability in long-pipeline gas systems through the development of trend curves over time for the attributes of corrosion wear, which are related to the length, width, and depth of the defect. In addition, Risk-Based Inspection (RBI) is applied in the most favorable numerical failure values according to the location of the defect, with the aim of analyzing the structural reliability and the expected useful life of the gas pipeline. To do this, it was necessary to use the data provided by pig readings in 2008, 2012 and 2018 by an instrumented pig, type Magnetic Flux Leakage (MFL), inspecting a gas pipeline with the finality to measure wall thickness. The 56 km long and 18 in diameter pipeline is partly onshore and partly offshore. Also, the pipeline anomalies are standardized according to the standards established in POF [1]. It is important to emphasize that the methodology described in this article can be used in the industry where the prevention of leakage incidents, the predictability of maintenance, and the elaboration of the respective inspection plans are required, since it has been theoretically possible to calculate the probability of failure in time beyond the respective impact on risk for the operational variables presented.

**Keywords:** smart pigs, RBI, structural reliability, failure probability, gas pipelines.

## 1 Introduction

Land and sea pipeline systems are utilized for the transportation of natural gas, crude oil, and derivatives. The implementation of periodic assessments utilizing predictive maintenance is of critical importance for the purpose of ensuring the safety and operability of the built infrastructure.

The most recent research, as presented in Filho et al. [2], indicates that corrosion defects in oil and gas pipelines can potentially compromise the safety of these structures. Moreover, Nicoletti et al. [3] posit that inspection aimed at verifying metal loss represented by corrosion provides valuable data for the assessment of pipeline integrity.

One of the procedures for conducting an inspection of pipelines is to pass an instrumented pig, which is equipped with a Magnetic Flux Leakage (MFL) tool. As reported in Pandey [4], the loss of metal due to corrosion, whether internal or external, results in a disturbance in the magnetic field, which is proportional to the volume of material removed.

The MFL tools apply the flux leakage principle, which involves the use of a magnetization system that employs a magnetic field along the length of the tubing as the tool moves through the line. The defects result in

the corruption of the applied field, which in turn produces flow leakage. Sensors positioned on the pig's body are employed to quantify flow leakage, with the system recording and storing this data. Subsequently, the measurements undergo analysis to estimate the geometric defect and severity (Thom [5]).

The application of algorithms enables the determination of the probability of failure, as well as the risk of failure and structural reliability. In this context, the length, width, and depth of the defect, which represent the loss of thickness of the pipeline, are employed in accordance with the precision of the instrumented pig.

Firstly, the conventional method entails calculating the probability of failure over time based on a Weibull distribution function. This is achieved by determining the shape parameter $\beta$ and scale parameter $\eta$, which allows for the identification of the most and least favorable wear positions in the gas pipeline.

This methodology enables the acquisition of input data for risk-based inspection (RBI), which is employed to estimate the risk by means of failure pressure analysis models. These models are utilized to calculate the remaining resistance of pipelines that are subject to corrosion in accordance with the standards Modified B31G, Shell 92, and DNV-99. This is accomplished through the utilization of the Monte Carlo method. As reported in Abubakirova et al. [6], the RBI is a method that is becoming increasingly popular and reliable for the evaluation and development of inspection plans.

Figure 1 provides a concise overview of the flow diagram utilized in the failure probability calculation model applied to gas pipelines.

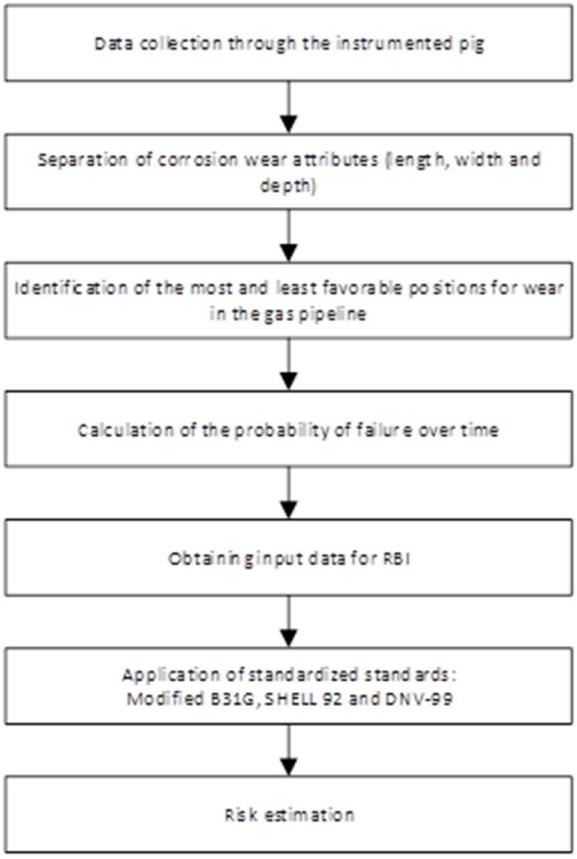



Figure 1. Flow diagram utilized in the failure probability calculation model applied to gas pipelines.

A subsequent review of more recent bibliographic references revealed that Amaya et al. [7] discusses the selection of reliability models in corroded pipelines for future intervention strategies. Furthermore, Zelmati et al. [8] presents a study that is related to the corrosion rate during the evaluation of the remaining useful life of pipes at the end of their useful life. This study proves to be fundamental for calculating the interval between two consecutive inspections.

# 2 Materials and methods

The structural reliability of gas pipelines is estimated through three readings obtained by field operations through the passage of the MFL-type instrumented pig. These readings collect the attributes of length, width, and depth of the defect (loss of thickness), which are then used to verify the behavior of the pipeline at risk of failure. In the interaction between these defects, the use of the ASME B31G [9] standard is required.

## 2.1 Interface with the Python language

In order to facilitate the analysis of data captured by the pig, an algorithm was developed in the Python programing language. The selection of Python as the application language was based on its versatility, speed of development, and the availability of additional libraries to assist in program development.

The program operates from the operating system terminal and accepts input data in Excel format, which was collected by the instrumented pig. In addition, it accepts a series of additional parameters that determine the resulting output data.

Table 1 depicts the behavior and distribution of the data following the respective treatment. It can be observed that the loss of thickness is expressed as a percentage. In accordance with the POF [1] standard, a pipeline is condemned for operation when the loss of thickness exceeds 80%. This standard aims for intervention and corrective maintenance.

Table 1. Data sample adjusted and organized using the Python programming language.

| 2008 | | | | 2012 | | | | 2018 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Longitudinal Distance [m] | Thickness Loss (%) | Corrosion Defect Length L [mm] | Corrosion Defect Width W [mm] | Longitudinal Distance [m] | Thickness Loss (%) | Corrosion Defect Length L [mm] | Corrosion Defect Width W [mm] | Longitudinal Distance [m] | Thickness Loss (%) | Corrosion Defect Length L [mm] | Corrosion Defect Width W [mm] |
| 12,846.86 | 10 | 18 | 17 | 12,846.15 | 10 | 20 | 18 | 12,829.06 | 27 | 35 | 19 |
| 12,848.94 | 10 | 12 | 18 | 12,848.69 | 10 | 12 | 18 | 12,848.70 | 12 | 14 | 20 |
| 12,850.84 | 10 | 17 | 18 | 12,850.68 | 11 | 21 | 18 | 12,850.85 | 20 | 37 | 26 |
| 12,859.93 | 11 | 16 | 18 | 12,866.00 | 11 | 25 | 18 | 12,862.81 | 19 | 44 | 38 |
| 12,967.69 | 11 | 17 | 17 | 12,978.84 | 15 | 34 | 18 | 12,995.65 | 18 | 43 | 34 |
| 38,735.76 | 10 | 12 | 18 | 38,708.77 | 10 | 12 | 18 | 38,677.94 | 17 | 13 | 20 |
| 38,734.18 | 10 | 15 | 17 | 38,693.14 | 10 | 21 | 18 | 38,678.05 | 21 | 31 | 29 |
| 38,749.53 | 10 | 16 | 17 | 38,750.86 | 10 | 18 | 18 | 38,750.60 | 23 | 35 | 34 |
| 38,768.09 | 10 | 15 | 18 | 38,774.75 | 10 | 16 | 18 | 38,774.47 | 20 | 34 | 36 |
| 38,808.68 | 12 | 16 | 17 | 38,823.03 | 12 | 16 | 18 | 38,822.99 | 25 | 32 | 20 |

## 2.2 Activity sequencing

Once the presented result was obtained, the correspondence between the events raised by the pig and the appropriate data was performed by means of checks carried out in different inspection years, in accordance with the following steps:

a) A region of tolerance for the pig reading is calculated in relation to the reference year (in this case 2018, as it is the most recent inspection) using the current reading position (Longitudinal distance) multiplied by the instrument precision (0.25%), as indicated in the equipment manual.

b) Consequently, the position readings conducted in years disparate from the reference year must be within the region previously demonstrated and have the same classification as the failure event presented.

c) To calculate the parameters of the Weibull distribution (β and η), which are related to the concepts presented in Thom [10];

d) Subsequently, the probability of failures is calculated using the conventional method, as outlined in Equation 1.

$$F(t) = \int_{-\infty}^{t} f(t)dt = 1 - e^{-(t/\eta)^{\beta}} \tag{1}$$

e) In the case of the RBI calculations, in addition to the standardized standards Modified B31G, Shell 92 and DNV-99, the limit state function was also used to calculate the probability of failures by the Monte Carlo method, by comparing the failure pressure and the operating pressure.

# 3 Results

According to what was presented in Thom et al. [11] we have.

## 3.1 Probability of failure determined with three pipeline pigging operations

After optimizing and organizing the data based on the three MFL pig readings (2008-2012-2018), according to the attribute type, with the values of material loss over time, the location of the defect and the accuracy of the instrumented pig, it was possible to generate the results.

The probability of failure was calculated over a period of 100 years of operation for the length, width and thickness of the corrosion, respectively. At the MFL pig position of 12,742.96 m, the most favorable conditions for material loss were identified in terms of length and depth, while for the average width of the corrosion cavity it was 12,846.42 m. These values serve as input data for the RBI procedure.

This technical survey is of great importance, as it estimates the useful life of the infrastructure and identifies the points most vulnerable to collapse over time.

## 3.2 Probability of failure determined with two pipeline pigging operations

In order to expand the amount of data employed and to observe the behavior of the resulting curves, two consecutive MFL pig inspections were conducted (2008-2012, 2012-2018 and 2008-2018). These inspections were prepared according to the technical guidelines mentioned above.

At the MFL pig positions of 12,784.70 m and 103.44 m, the most favorable conditions for metal loss in terms of length and depth were identified, while the average width of the corrosion cavity was 12,771.99 m. These values also serve as input data for the RBI procedure.

## 3.3 Application of Risk-Based Inspection (RBI)

As previously noted, the most favorable values at the wear location points for the attributes of length and depth of the defect, as well as the average width of the corrosion pit, serve as the input data for RBI in three and two pig inspections.

In this manner, the standardized routines Modified B31G, Shell 92, and DNV-99 are employed to calculate the results presented in Table 3 at one-year intervals. The probability of failure is determined until the final time of 20 years.

In the Risk-Based Inspection (RBI) analysis for the pipe, it is observed that up to 10 years, the three standards present values close to zero for the probability of failure. Moving forward, the Shell 92 failure pressure analysis model presents more cautious results that require attention.

Accordingly, the theoretical and mathematical modeling presented indicate that, even when considering a user inspection every five years or a mandatory inspection every ten years, the 56 km pipeline would remain capable of withstanding the respective operating pressure, despite the evolution of loss of material by corrosion over time.

# 4 Discussion

## 4.1 Weibull distribution parameters

Table 2 presents some values of the shape parameter (β) of the failure model in the Weibull distribution above 1. This indicates that the component is in the aging zone of the bathtub curve. Consequently, the probability of failure is high.

However, when the characteristic life (η - scale parameter) in the Weibull distribution is relatively high in comparison to the others, it results in a favorable trend in the probability of pipeline failure.

Table 2. Parameters in the Weibull distribution

| attribute | predictive maintenance | | defect location (m) | | Weibull distribution | | Probability of failure (%) |
|---|---|---|---|---|---|---|---|
| | three pigging | two pigging | more favorable | less favorable | β | η | 100 years |
| length | X | | 12,742.96 | | 1.41 | 29.53 | 99.63 |
| | | | | 12,967.69 | 0.91 | 69.60 | 75.05 |
| width | X | | 12,846.42 | | 1.35 | 43.71 | 95.25 |
| | | | | 12,742.96 | 0.91 | 63.86 | 77.80 |
| loss of thickness | X | | 12,742.96 | | 1.41 | 24.61 | 99.93 |
| | | | | 12,710.81 | 0.93 | 38.21 | 91.38 |
| length | | X | 12,784.70 | | 1.44 | 22.48 | 99.98 |
| | | | | 56,144.60 | 0.99 | 87.28 | 68.14 |
| width | | X | 12,771.99 | | 1.44 | 33.72 | 99.16 |
| | | | | 12,785.41 | 1.28 | 123.57 | 53.37 |
| loss of thickness | | X | 103.44 | | 1.44 | 18.73 | 100.00 |
| | | | | 12,850.18 | 0.73 | 34.30 | 88.80 |

### 4.2 Impact on risk

In the Risk-Based Inspection (RBI) analysis for the gas pipeline, it is observed that the Shell 92 failure pressure analysis model presents more conservative results.

Table 3 also illustrates the range of failure probabilities and their associated consequences, as outlined by Mokhtar et al. [12]. It can be observed that the risk is considered to be higher after 11 years of use for three pigging and 10 years of use for two pigging.

Table 3. Impact on safety risk

| | Probability of failure (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | three pigging | | | | two pigging | | | |
| year | Shell 92 | B31G Modificada | DNV-99 | Impact on risk | Shell 92 | B31G Modificada | DNV-99 | Impact on risk |
| 1 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| 2 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| 3 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| 4 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| 5 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| 6 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| 7 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| 8 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| 9 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | |
| 10 | 0.00 | 0.00 | 0.00 | | 0.01 | 0.00 | 0.00 | High |
| 11 | 0.31 | 0.06 | 0.14 | High | 0.34 | 0.07 | 0.15 | High |
| 12 | 1.62 | 0.64 | 0.70 | High | 1.66 | 0.66 | 0.71 | High |
| 13 | 3.48 | 1.93 | 1.46 | High | 3.49 | 1.94 | 1.47 | High |
| 14 | 5.26 | 3.49 | 2.20 | High | 5.27 | 3.51 | 2.20 | High |
| 15 | 6.76 | 5.02 | 2.82 | High | 6.75 | 5.02 | 2.81 | High |
| 16 | 8.03 | 6.40 | 3.34 | High | 8.02 | 6.38 | 3.34 | High |
| 17 | 9.08 | 7.55 | 3.80 | High | 9.08 | 7.52 | 3.79 | High |
| 18 | 9.97 | 8.57 | 4.17 | High | 9.96 | 8.55 | 4.18 | High |
| 19 | 10.71 | 9.43 | 4.51 | High | 10.71 | 9.42 | 4.51 | High |
| 20 | 11.40 | 10.20 | 4.82 | High | 11.38 | 10.19 | 4.81 | High |

## 5 Conclusions

In this study, a real database of in-pipe inspection with MFL pigs was employed to develop and validate structural reliability tools for assessing the probability of failures using the conventional method and the Monte Carlo method. The objective was to establish an inspection program for long-distance gas pipeline systems based on quantitative risk assessment.

It is recommended that, for reasons of safety, the pipeline be inspected at the most critical levels in the event

of defects with different time intervals. In this regard, it is prudent to consult the technical guidance in POF [1] in relation to the other positions. Furthermore, it is necessary to conduct a more thorough examination of the cause of non-measurement in sections of the pipeline system that are being inspected.

The results indicate that the duct has a relatively long useful life (60 years until wall collapse) due to the high values of the diameter and thickness of the duct wall. This is a duct with a very conservative dimension. These results are in accordance with numerical studies of the sensitivity of random variables, whose objective is to verify the greater or lesser influence of these variables on the failure of a pipeline. The existing literature indicates that the depth of the defect, the internal pressure of the fluid, the diameter, and the thickness of the pipeline wall have a significant impact on the probability of pipeline failure.

Moreover, the probability of failure over time when employing two MFL pigging operations was found to be comparable to that of the previous operation. In this case, the use of fewer inspection processes could result in a reduction in predictive maintenance costs.

Furthermore, it is often challenging to conduct a reliability assessment based on failure data due to the lack of observed or recorded failures in history. In such instances, the inspection data typically represents a collection of information regarding the degradation of the pipeline. The data provides insights into the corrosion of the pipeline within the selected period, which can be used to inform the reliability assessment.

As future studies are conducted, it is recommended that a cost-benefit analysis be conducted to verify whether it is possible to reduce pigging operations while maintaining the same or equivalent technical and operational result.

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