1. Introduction

Natural gas (NG) is poised to capture a larger share of the world’s energy demand. Liquefied Natural Gas (LNG) plays an important role by linking overseas producers and consumers and also as security of supply by offering several choices of suppliers. [1]

One defining characteristic of pipeline networks is that they become more valuable with size as more entities join the network. Thus, the NG pipeline industry is starting to implement comprehensive integrity management practices to meet the demands of new regulatory imperatives and public interests. Once such threats are identified, the pipeline operator shall characterize the degree of risk associated with the threat as a means of prioritizing responses, identify suitable methods to assess the presence of the threat, and develop appropriate mitigations.

Interest has arisen regarding fatigue as one such possible integrity threat but just a small part is due to induced fatigue as the use of pressure cycling operation to improve energy efficiency is far from being applied. To provide a more energy efficient process, aiming for energy reduction in both cost and environmental, certain changes have to be made. One of them can be adjusting the consumption profile of NG injected in the network. This study is going to be focus on the changes have to be made. One of them can be adjusting the consumption profile of NG injected in the network.

2. Fundamental Concepts

2.1 Fracture Mechanics

The fracture process is related with nonlinear deformation, as the zone where the fracture process takes place, is the region around the crack tip where dislocation motions occur. The zone size is characterized by the number of grain sizes for brittle fracture or by either inclusion or second phase particle spacing for ductile fracture. [2] Different theories have been advanced to describe the fracture process in order to developed predictive capabilities, like Linear Elastic Fracture Mechanics (LEFM) and Elastic-Plastic Fracture Mechanics (EPFM) [3]. LEFM is used to predict material failure when response to the load is elastic and the fracture response is brittle. LEFM uses the strain energy release rate, \( \dot{G} \), or the stress intensity factor, \( K \), as a fracture criterion. Considering a homogeneous linear-elastic material, the stress distribution in the region in front of the crack of a plate in tensile loading are:

\[
\sigma_x = \frac{K_1}{\sqrt{2\pi r}} \left[ \cos \frac{\theta}{2} \left( 1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \right] \\
\sigma_y = \frac{K_1}{\sqrt{2\pi r}} \left[ \cos \frac{\theta}{2} \left( 1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \right] \\
\tau_{xy} = \frac{K_1}{\sqrt{2\pi r}} \left[ \sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \right]
\]

These equations describe the stress concentration in the crack tip region in function of the toughness. However, they represent a singularity for \( r = 0 \) where \( \sigma \to \infty \). As the.
Failure Assessment on Effects of Pressure Cycle Induced Fatigue on Natural Gas Pipelines

$r$ is getting smaller, the local stress increases, reaching the yield strength of the material.

This situation leaves the crack tip inside a region of plastically deformed material, where stress relieved and linear solutions are not the most acceptable. Elastic-Plastic Fracture Mechanics is an alternative developed for the study of the behaviour of non-linear materials and exhibit considerable plasticity in the crack tip of a flaw, i.e., materials under large-scale or general yielding conditions. In 1968 Rice developed another EPFM parameter called the $J$-integral. It describes the elastic-plastic deformation around the crack tip to be nonlinear elastic. The $J$-integral was shown to be equivalent to $\psi$ for linear elastic deformation and to the crack tip opening displacement for elastic-plastic deformation and is also a nonlinear stress intensity parameter, for materials whose mechanical behaviour is described by the Ramberg-Osgood equation.

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + a \left( \frac{\sigma}{\sigma_0} \right)^n$$  \hspace{1cm} (4)

$J$-Integral characterizes the stress field and its fracture conditions in the neighbourhood of the crack.

$$J = -\int_V \left[ H \frac{\partial \bar{q}}{\partial x} + (f \cdot \frac{\partial u}{\partial x}) \cdot \bar{q} \right] \partial V$$  \hspace{1cm} (5)

1.2 Fatigue Failure

Fracture mechanics often plays a role in life prediction of components that are subject to time dependent crack growth mechanisms such as fatigue. The rate of cracking can be correlated with fracture mechanics parameters such as the stress-intensity factor, and the critical crack size for failure can be computed if the fracture toughness is known. Damage tolerance, as its name suggests, entails allowing subcritical flaws to remain in a structure. Repairing flawed material or scrapping a flawed structure is expensive and is often unnecessary.

Fatigue is a process of structural degradation caused by fluctuations of stress cycles. Stresses are typically amplified locally by structural discontinuities, geometric notches, surface irregularities, defects, or metallurgical non-homogeneities. Fatigue may occur in three sequential stages, the formation of a crack, called initiation, the stable incremental enlargement of the crack in service, called propagation and the rapid unstable fracture, i.e., failure. A typical operating pressure spectrum for a natural gas pipeline may look something like what is shown below.

Typically the largest cyclical component is seasonal, which means it occurs once per year. The pressure signal is stochastic, meaning it consists of an apparently random mix of signal amplitudes. Although the load spectrum is already much more realistic than the harmonic loading with constant frequency and amplitude, practical loading is mostly random. Prediction of fatigue life is only possible after this random load is transferred into a harmonic load spectrum, with known frequencies and amplitudes. Several experiments have shown that the crack length is an exponential function of the number of cycles. This means that crack growth is very slow until the final stage of fatigue life, where a relative short number of cycles will result in fast crack growth leading to failure. The initial fatigue crack length seems to be a very important parameter for the fatigue life. To predict the fatigue life of structures, crack growth models have been proposed, which relate $\frac{da}{dN}$ to stress amplitude or maximum stress, which can be expressed by the stress intensity factor, where stresses are low. Microstructural models relate the
crack grow rate to microstructural parameters, such as the distance between striations. The Paris Law is the simplest fatigue crack growth law. The equation has the form:

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

(6)

For low and high values of $\Delta K$, Paris law does not describe accurately the crack growth rate. For $\Delta K = K_{IS}$, the lower limit, a crack grows extremely slowly, hampered by the roughness of the crack faces. For still smaller values of $\Delta K$, the crack growth is extremely small but not completely zero. For high values of $\Delta K$, crack growth is much faster than predicted by the Paris law.

### 1.3 Pipeline Mechanics

Pipelines must be able to withstand a variety of loads. However, buried pipelines are essentially restrained elements, as the displacement of the pipe is restricted by the soil around it. Thus, for buried pipelines, the major stress is caused by the internal pressure and this hoop stress is usually the major design consideration. [1] Typically for calculation purposes pipelines are considered to be in a bi-axial state called plane stress. The hoop stress, $\sigma_H$, acts around the circumference of the pipe and the longitudinal stress, $\sigma_L$, is directed along the long axis of the pipe. In general, there is a third stress, a shear stress, which could be acting on the edges of the above unit section, but this is not normally significant and is usually neglected in calculations of transmission pipelines.

![Figure 5 - Pipe stresses under internal Pressure. [7]](image)

Pipelines with diameter to wall thickness ratios greater than 20, typical of transmission pipelines, are considered “thin-walled” as the distribution of normal stress perpendicular to the surface is essentially uniform throughout the wall thickness. For isotropic materials, the relationship between stress and strain under plane stress conditions is expressed as:

$$\left(\frac{\varepsilon_H}{\varepsilon_L}\right) = \frac{1}{E} \left[ \frac{1}{1-\nu} \left(\frac{\sigma_H}{\sigma_L}\right) \right]$$

(7)

### 3. Pressure Cycle Simulation

While companies do their best to estimate demand for NG, it is nearly impossible to predict the exact quantity a given facility will consume. Pipelines and utilities require industrial companies to utilize nomination and balancing programs to manage gas flow and minimize operational imbalances. The concept of physical quantity of gas starts to take place.

The LNG Terminal operation is highly conditioned on the needs of the NG Portuguese system, especially those conducted by the electricity market and LNG global market. This constraint has not allowed a proper rationalization of distribution. For the purpose of the study, two scenarios of nominations were chosen. The first one it is expected to induce pressure cycle profiles with large amplitudes and the second with low amplitudes. These two cases are trying to emulate the reality.

<table>
<thead>
<tr>
<th>Table 1 - Total LNG Terminal gas nominations for two scenario studies.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Periods</strong></td>
</tr>
<tr>
<td>Saturday $m^3(n)$</td>
</tr>
<tr>
<td>Sunday $m^3(n)$</td>
</tr>
<tr>
<td>Monday to Friday $m^3(n)$</td>
</tr>
</tbody>
</table>

There are considered only two entries of NG in the network, namely, through Campo Maior (from Maghreb-Europe Gas Pipeline) and through the LNG Terminal. The other two entries presented in section 2 (Valença do Minho and UGS) are not considered due to the fact that Valença do Minho has a limited capacity and the flow rates are really low, and for simplification purposes, there are no injection or withdraw from UGS.

The gas flow values are the inputs to the software SIMONE for simulating the pressure cycle profiles within the pipelines. The maximum projected working pressure (84 bar) and the minimum pressure in every single distribution point in the network (50 bar) were used as boundaries conditions. Moreover, a static initial state was used in order to have the first iteration for the simulation to start.

![Figure 6 - Scenario 1: Pressure Cycle Profiles, during a week.](image)

![Figure 7 - Scenario 2: Pressure Cycle Profiles, during a week.](image)
For this reason, and because the goal of the study is to try to make an assessment of the worst case possible that could happen to the pipeline, the scenario 1 is going to be chosen for doing the fatigue testing, integrity assessment and for modelling the crack propagation.

4. Experimental Testing

 Though, fracture mechanics tests in real scale are extremely costly and difficult to do in practice, so the alternative is to use small scaled dimension specimens. In laboratory testing it is considered the similarity of the stress-strain field between the specimen and the real scale structure, which allows correlating the experimental results obtained to cracked structures real conditions.

Two tests were made to infer certain characteristics of the material used on pipes. The specimens made for the testing were from an 28 inch (711.1 millimetres) steel pipe with 12.9 millimetres of thickness. This component has already been working in branch L03000 close to Monforte, Portugal. It is made with API 5L Grade X70 steel from EUROPIPE.

The tensile testing was made in the laboratories of the Instituto Politécnico de Setubal and it was used an Instron 1432 machine, with a load cell of $100\,kN$.

For fatigue characterization the standard ASTM E647 – Measure of Fatigue Crack Growth Rates was followed. A camera was attached to the Universal Testing Machine in order to take pictures of the crack propagating through the specimen. Those pictures were treated after in order to infer the fatigue crack growth rate with the increase of the number of cycles.

Table 2 - Results obtained from the tensile testing.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Longitudinal</th>
<th>Radial / Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>207</td>
<td>207</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>513</td>
<td>551</td>
</tr>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>582</td>
<td>676</td>
</tr>
<tr>
<td>Yield-to-Tensile Ratio</td>
<td>0.88</td>
<td>0.84</td>
</tr>
<tr>
<td>Uniform Elongation (%)</td>
<td>7.00</td>
<td>8.51</td>
</tr>
</tbody>
</table>
Table 3 - Fatigue Crack Propagation Test results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Material parameter, ( C )</th>
<th>Material parameter, ( m )</th>
<th>Number of cycles to fail</th>
<th>( \Delta K_{th} ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 4 \times 10^{-13} )</td>
<td>3.94</td>
<td>63161</td>
<td>21.92</td>
</tr>
<tr>
<td>2</td>
<td>( 4 \times 10^{-12} )</td>
<td>3.28</td>
<td>55800</td>
<td>19.52</td>
</tr>
</tbody>
</table>

The numerical calculation of the \( J \) and \( K \) (Mode I) were performed. The results were obtained by using XFEM and Contour Integral techniques. For both cases, the number of contours were 5. This parameter controls the number of element rings around the crack tip that construct the contour domains for the contour integral calculation. The contour integral calculation is the most important aspect in stationary crack analysis since it gives the measure to assess critical crack size. The stress intensity factors in ABAQUS® are calculated along the crack front for a finite number of positions, so called contour integral evaluation points. These points are chosen automatically by ABAQUS® where the crack front intersects the element boundaries. Several contour integral calculations are performed at each evaluation point for all specified element rings.

Figure 12 – Details from the specimen after the fatigue failure.

5. Numerical Modelling

In order to obtain mechanical properties to ensure that the laboratory results and the integrity assessments procedures are similar, it has been model with the software ABAQUS® two scenarios. The first one the defect is placed perpendicular to the direction of the pipe, so it would suffer more from longitudinal stresses. In the other hand, in the second scenario, the seem is placed along the direction of the pipe, so it would suffer more from hoop stresses. The representation from the pipeline to ABAQUS® models could be approximated with to Single Edge Notched Tensile Plate (SENT) – Scenario 1 or to a Center-cracked tensile plate (CCT) – Scenario 2.

The first partial contour domain is the elements surrounding the crack tip element. The next partial contour domain contains the first domain and the next element ring directly connected to the first contour domain. Each subsequent contour domain is built up by adding the next element ring to the previous contour domain. Theoretically, the contour integral calculation is independent of the size of the contour domain as long as the crack faces are parallel. But because of the approximation with a finite element solution, the \( K \) and \( J \) for the different element rings will vary and should converge as the domain is increased. Therefore the first element ring was discarded in the analyses because of their large deviation. The results can be observed below.

Figure 13 - Scenario 1: (a) Schematic representation (b) ABAQUS® models (FEM-Contour Integral and XFEM)

Figure 14 - Single Edge Notched Testing simulated with: (a) FEM (b) XFEM.

Figure 15 – Scenario 1: \( K \) and \( J \) parameters in function of the Load. The values are for \( a = 2 \text{mm} \).
It is observed that the values from the simulation are lower than those obtained by the SENT simulation. Due to this fact, the values that are going to be applied to perform the assessment based on $J$-integral values are those obtained by the SENT simulation.

The $J$-based Failure Assessment Diagram can be done starting adjusting a curve to the values can are result from the ABAQUS® simulation. A quadratic curve fit is expected since $J$ is proportional to $K$ which is linear in the elastic range. The elastic $J$ trend is computed using the curve-fit and compared to the next several $J$ to confirm that these results are in the expected elastic range and that the curve-fit is valid. In a typical elastic-plastic analysis without a crack, the initial load increments can be large since equilibrium convergence is expected. However, for an elastic-plastic fracture analysis with a crack several small load increments are needed at the beginning of the analysis to ensure that there will be $J$ results in the elastic range. The maximum load must be high enough to create yielding at the crack front, which is usually a much higher load value than the operating or design load. The curve fit is used to extrapolate and infer the elastic $J$ trend for the higher load increments.

The nominal load value is obtained by using the material specific FAD equation evaluated at $L_r = 1$. When the material specific FAD curve equation is evaluated at $L_r = 1$, it takes this form given by:

$$J_{total} = J_{elastic} + \left[ 1 + \frac{0.002E}{\sigma_y} \right] \left[ 1 + \frac{0.5 \sigma_y}{0.002E} \right] \left( \frac{W}{r} \right)^{0.5}$$

where $W$ is the width of the plate and $r$ is the radius of the crack.

### Figure 16
Scenario 1: $K$ and $J$ parameters in function of the crack length. The values are for $a = 2 \text{mm}$.

### Figure 17
(a) Schematic representation (b) ABAQUS® models (FEM-Contour Integral and XFEM)

### Figure 18
Scenario 2: (a) $K$ and $J$ parameters in function of the Load. The values are for $a = 2 \text{mm}$.

(b) $K$ and $J$ parameters in function of the crack length. The values are for $a = 2 \text{mm}$.

### Figure 19
Center-cracked Tensile Plate simulated with XFEM.

### Figure 20
Infer the elastic $J$ trend using the curve fit.
Failure Assessment on Effects of Pressure Cycle Induced Fatigue on Natural Gas Pipelines

The reference stress geometric factor, $F$, is defined as the ratio of the yield stress to the nominal load obtained at $L_r = 1$.

$$F = \frac{\sigma_y}{\sigma_{nominal}|L_r=1}$$  \hspace{1cm} (9)

The nominal load value is obtained from the intersection point. It gives the reference stress that satisfies the material specific FAD equation at $L_r = 1$. The reference stress and $L_r$ can be computed for analysis increment to obtain the analysis specific and material specific values. The reference stress, at each load increment is given by:

$$\sigma_{ref} = F\sigma_i$$  \hspace{1cm} (10)

The FAD curve is obtained by using:

$$L_r = \frac{\sigma_{ref}}{\sigma_y} = \frac{F\sigma_i}{\sigma_y}$$  \hspace{1cm} (11)

$$K_r = \sqrt{\frac{J_{elastic}}{J_{total}}}$$  \hspace{1cm} (12)

Where $J_{total}$ are the elastic-plastic analysis $J$ results, and the $J_{elastic}$ Values were obtained from the curve-fit to the first few result increments in the elastic range. The evaluation points are computed using the stress intensity from the elastic analysis and the reference stress at the given load. The $J$-based FAD can be shown below. The points are representative of the ratio $a/W$, which represents how much a structure is cracked.

6. Integrity Assessment and Structural Reliability

Nowadays, it is consensus that every single polycrystalline metallic structure contains defects, which not means they put their structure in risk of integrity. The fitness-for-purpose approach is based in fracture mechanics and has by objective evaluate the impact caused by a defect in the performance in service of a certain structure. A FPP approach presents a tremendous economic potential as for it. It is possible to define safe operation conditions and even extend the structure’s life cycle. Natural gas, Petroleum and Nuclear industries motivated the establishments of procedures for these approach where the most used are the BS7910 from British Standard Institute, the API 579 from the American Petroleum Institute and the R6 procedure from the Nuclear Fuels & Co. from United Kingdom (former Central Electricity Generating Board). None of these approaches stated before globe all evaluation techniques or give us the best guidelines. In fact, there is divergence in the results obtained by different approach methods, as they use different formulations.

6.1 Failure Assessment Diagram

Through a graph it is defined regions of safe operation and unsafe operation to the structure. The vertical axis represents the toughness ratio as a coefficient between the stress intensity factor applied and the fracture toughness of the material. The load ratio is presented in the horizontal axis, as the coefficient between the applied stress and a reference stress. When the stress applied in equal to the reference stress then the structure starts to plastically collapse.

$$K_r = \frac{K_i}{K_{mat}}$$  \hspace{1cm} (13)

$$L_r = \frac{\sigma}{\sigma_{ref}}$$  \hspace{1cm} (14)

There are two modes of failure represented in this diagram, the vertical axis represents the totally fragile failure and in the horizontal axis, it is represented the likelihood plastic collapse [7]. In the transition region between failure modes, there is a mixed failure mode, fragile failure governed by LEFM and plastic collapse governed by the limit load that the material supports. In the original R6 procedure, the interpolation curve for both mechanisms is obtained by the strip yield model, purposed by Dugdale. This model states a solution for a problem in plain strain of a crack in an infinite plate with an elastic-plastic material subjected to tensile forces.

$$K_r = L_r \left( \frac{8}{\pi^2} \ln \sec \left( \frac{\pi L_r}{2} \right) \right)^{1/2}$$  \hspace{1cm} (15)

![Figure 22 - J-Based Failure Assessment Diagram.](image)

![Figure 23 - Schematic representation of the FAD.](image)
6.2 Structural Reliability

For structural reliability analysis, a deterministic description is necessary for component failure assessment, while a statistical analysis is required computing the Probability of Failure (POF) from the scatter of the random input quantities. Probability Fracture Mechanics (PFM) deals with the assessment of the reliability of the structures containing crack-like defects in terms of probabilities attributed to a certain event of failure. It is well accepted that certain parameters involved in a fracture mechanics analysis are probabilistically distributed variables. Material properties always exhibit scatter, cracks sizes are statistical variables and loadings may also be random or pseudo-random. Given the input variables \( x = (x_1, x_2, ..., x_N) \) with used defined Probability Density Function (PDF), \( f(x_1) ... f(x_N) \), the POF is defined as:

\[
P_f = \int_{g(x_1, ..., x_N) \leq 0} f(x_1) ... f(x_N) \, dx_1 ... dx_N
\]

(16)

The failure function \( g(x_1, ..., x_N) \) divides the domain of the variables into two parts:

\[
\begin{align*}
\text{Failure Domain} & \quad g(x_1, ..., x_N) \leq 0 \\
\text{Safe domain} & \quad g(x_1, ..., x_N) > 0
\end{align*}
\]

(17)

The integration has to be carried out over the failure domain \( g(x_1, ..., x_N) \leq 0 \). For simplicity, variables are assumed to be stochastically independent for the POF calculation. The failure criterion is based on the Failure Assessment Diagram, whereas the limit state equation \( g(x_1, ..., x_N) \) can be broken down into two separate functions, according to:

\[
g(x_1, ..., x_N) = (K_I - K_I)^2 - K_I, \quad \Delta L \leq L_{max}
\]

(18)

In most of the cases, the detection of defects in pipelines is performed using intelligent pigs, as a part of the normal operation and maintenance program. During inspections, not all defects can be identified due to the sensitivity of the tool. The process of inspection and repair of a pipeline at a given time interval will change the distribution of crack depth and length because some of the detected cracks will be repaired. The exact distribution will depend upon the repair strategy adopted, the frequency of inspection and the sensitivity of the pig. The remaining cracks will not lead to failure but those missed by the inspection tool might cause gas leakage or rupture of the pipeline. Probability of Detection (POD) is defined as:

\[
P_{D/A} = 1 - e^{-\lambda a}
\]

(19)

Hence, the detectable depth of the pig follows the exponential distribution function and both the average detectable size and the standard deviation equal to \(1/\lambda\).

The POF can be evaluated by numerical integration, the First Order/Second Order Reliability Method (FORM/SORM) and by Monte-Carlo Simulation (MCS) [5].

6.3 Results

6.3.1 BS 7910

The growth of a known dimension crack over the cycles. Starting with a crack depth of 0.1 mm, the assessment is made till the crack reaches 6 mm. The following results were obtained, for the two levels considered.

When the crack depth reaches certain value, the point is placed in the unsafe zone, meaning that the structure has to be repaired, remediated or replace. An interesting observation is that internal cracks oriented axially fail easier than external ones and their failure compared with the circumferential oriented flaws is less straight-forward, as they follow a curve-like shape.

6.3.2 Structural Reliability

As usual, this results are going to be done for the dimensions of the pipelines on trunckline L12000, mostly for 28 inch pipelines due to the fact that they are the most used diameter in that line. The cracks to be analysed are assumed to be longitudinal and circumferentially oriented as maximum hoop stress is normal to the orientation of the flaw where brittle fracture and fatigue failure will most likely occur.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Distribution type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Diameter</td>
<td>711</td>
<td>0</td>
<td>Fixed</td>
</tr>
<tr>
<td>Thickness</td>
<td>11.1</td>
<td>0</td>
<td>Fixed</td>
</tr>
<tr>
<td>Initial Crack Depth</td>
<td>1.5269</td>
<td>0.794</td>
<td>Log-normal</td>
</tr>
</tbody>
</table>
the limit state function. The POF given is $7.36 \times 10^{-4}$. The result is in good agreement with the analytical solution as the difference is below 2%. Also, using FORM, the POF is $7.31 \times 10^{-4}$ with $\beta = 3.182$.

7. Concluding remarks

The service demand for products transported through pipelines are inherently non-stationary. As a result, operating pressure levels vary from time to time. Variations in operating pressure produce variations in the hoop stress level in the pipeline, and can thus cause metal fatigue that could eventually lead to failure in service of the structure.

Generally, the fatigue life of a properly designed sound structure is quite long. Typically, millions of normal service-stress fluctuations are required for a failure to occur. In a pipeline the number of very large stress cycles (i.e., pressure cycles) is usually on the order of tens to hundreds of cycles per year, so one might expect that the potential for a pressure-cycle-induced fatigue failure in any pipeline would be insignificant. However, those variations on pressure cycle do not mean high amplitudes each cycle. The goal of this thesis is to infer the degree of exposure of a pipeline to fatigue induced by high amplitude pressure cycles (20-30 bar).

Nowadays, the fix capacity contract with the Algerian gas supplier is almost enough to supply the NGTN. However, as the economy activity increases (as expected), the need to inject NG in the network is going to occur. In this situation, a flexible LNT Terminal is the answer to fulfill all distribution points at a lower rate, than the one of the fix contract. For REN, an optimized profile emission leading to a more energy efficient process, aiming for energy reduction in both cost and environmental impact is essential. The LNG Terminal has several facilities that can be used rationally, as they can follow a rotation program within the company. This leads not only to the promotion of operating at maximum efficiency but also to avoid successive starts and stops of the equipment. This the focal point for the adequacy management of periods of higher flow rate emission of NG to the NGTN. Scenarios that create different pressure cycle profiles within the pipe were simulated. These scenarios allow understanding that it would be possible to daily save power and cost using optimized emission profiles.

Sending out the maximum gas flow during hours of lower electricity tariffs and using minimum injection rates, during day hours of higher electricity tariffs, induce a 5-10% cost saving per year in the LNG Terminal. The results obtained, through fatigue tests, numerical modelling and integrity assessment using fitness-for-purpose approaches concluded that, in normal operational conditions, the pipe would not fail due to pressure cycle induced fatigue.

The carried out approaches confirmed that the most critical flaws are longitudinal interior cracks and those that manufactures must be more aware as they cannot be repaired in-service. In terms of fatigue, the remnant life of the pipes in truckling L12000, according with the maximum crack depth allowed, is around 40 to 50 years. This is a convenient observation as the normal period of service is 50 years.

In terms of POF over the years, it is clear that, with time there is going to be bigger cracks so it is normal that the POF will increase.

It was also computed the POF with MCS. With this method, random numbers were generated to be inside

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Distribution type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Crack Length (mm)</td>
<td>11.136</td>
<td>5.068</td>
<td>Log-normal</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>6.897</td>
<td>0.608</td>
<td>Normal</td>
</tr>
<tr>
<td>Fracture Toughness (MPa √m)</td>
<td>84.195</td>
<td>37.869</td>
<td>Normal</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>532.104</td>
<td>18.899</td>
<td>Normal</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>628.988</td>
<td>47.456</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Analytically, the POF is equal to $7.29 \times 10^{-4}$. For calculating the POD, the parameter $\lambda$ can be defined as:

- Assuming the minimum detectable depth for the pig is 0.2 mm;
- The probability of detecting a defect of 30% of the thickness is 90%.

Thus, $\lambda$ takes the value, for each class:

$$P_D = 1 - e^{-\lambda(0.2)}$$

$$0.90 = 1 - e^{-\lambda(0.3)}$$

$$\lambda = \frac{\ln(1 - 0.9)}{0.3} = 0.2$$

This also implies the average detectable depth is $1/\lambda + 0.2$, in this case, 1.559 mm.
200 years in-service life. This matches reality as pipelines with more than 100 years old are still operative, as stated before in England and in The Netherlands).

Structural reliability analysis was carried out, assuming a certain known crack distribution. POF is strongly dependent on the distribution of the defects in the pipeline, in particular the crack depth. Other properties like yield strength, tensile strength and fracture toughness affects the value of the POF. The value of POF is relatively low and there was good agreement between the three methods applied (analytical, FORM and MCS). As predicted the bigger the crack, the higher the probability of detection of the same crack. However, sensitivity depends on the inspection tool used, and this can be a focal point in order to prevent some cracks to propagate catastrophically. Nevertheless, a structure like a pipeline can have long usage time, as NG is not very corrosive for because before being injected in the structure, certain corrosive elements, particularly Sulphur, are extracted from the fluid.

In order to guaranty the integrity, security, operability and increasing life of the NG transportation system, a Pipeline Integrity Management System may be implemented as a part of a methodology of Management Assets. Almost 90% of the assets cost of the NGTN are buried pipelines, so it is necessary to obtain equilibrium between security, maintenance costs and reliability. Implementing PIMS would benefit greatly REN. The main benefits are intangible and are related with the decrease of the probability of failure and accidents in the infrastructure, thus, reducing NG supply interruption, human related damages (injuries and death), damage in third-party infrastructures, civilian responsibility, negative impact in the image of the company, environmental impacts, OPEX costs and costs associated with the repair of the structure and loss of NG.

8. Future Work
For future work, more tests should be made in order to have a better sample of results, resulting in a more trustworthy study. Also, the study should be extended to off plane cracks (cracks that are not perpendicular or parallel to the applied load) in order to understand the relationship between crack propagation angle and the applied load. Modelling should be also carried out for curved structures in order to confirm the results obtained by the FFP approaches. As far as Structural Reliability is concerned, a more in-depth analysis of the POF should be carried out for cases where other distributions of cracks are used, as well to validate the concept with the data from intelligent ‘pigs’. Different inspection and repair criteria should be available in the simulation whereby an optimal maintenance strategy can be obtained by comparing different combinations of inspection and repair procedures. The simulation provides not only data on the probability of failure but also the predicted number of repairs required over the pipeline life thus providing data suitable for economic models of the pipeline management.

Acknowledgement
The author wish to acknowledge REN for allowing an academic internship in order to do this work and PhD Alberto Ferro and PhD Ricardo Batista for the collaboration and assistance though the work.

References