

Transient analysis helps IM for crater-type corrosion defects

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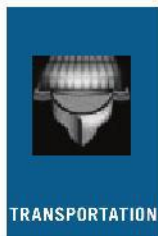
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Introducing transient analysis to pipeline integrity management (IM) is strongly recommended when crater-type corrosion defects are present and when threshold criteria are more rigorous than usual. Applying transient analysis to gas pipeline integrity management does not significantly increase the number of repairs, only the manner in which they are planned for, and therefore does not result in prohibitive additional costs.

Transient analysis, however, is not justified in integrity management of gas pipelines when all corrosion points are of pinhole type.

Structural-reliability model

Pipeline integrity management programs focus mainly on using inline inspection (ILI) tools, with significant progress in this field allowing detection of nearly all corrosion defects. ILI inspections typically display results as graphics showing the geodetic positions of the main corrosion defects and their dimensions. A number of standards estimate the failure stress of pipelines according to the geometrical dimensions of critical defects and guide repairs needed to return a particular line to its original maximum allowable operating pressure (MAOP).

Corrosion estimation

Comparing the size of defects in successive ILI inspection runs allows estimation of the failure stress of a corroded pipeline by monitoring corrosion rate.¹ A minimum of two sequential inspections are required to gauge corrosion rate, with repair priorities assuming a defect-by-defect linear evolution of corrosion depth (Equation 1 in accompanying equations box).

Rigorous monitoring of corrosion rate requires frequent ILI inspections. But this is an expensive proposition for large pipeline systems, and ILI tool programming must take limits on available resources into account. Operators of a pipeline that has only been inspected once must estimate corrosion growth rates heuristically or by using Bayesian approaches.²

FOLIAS FACTOR

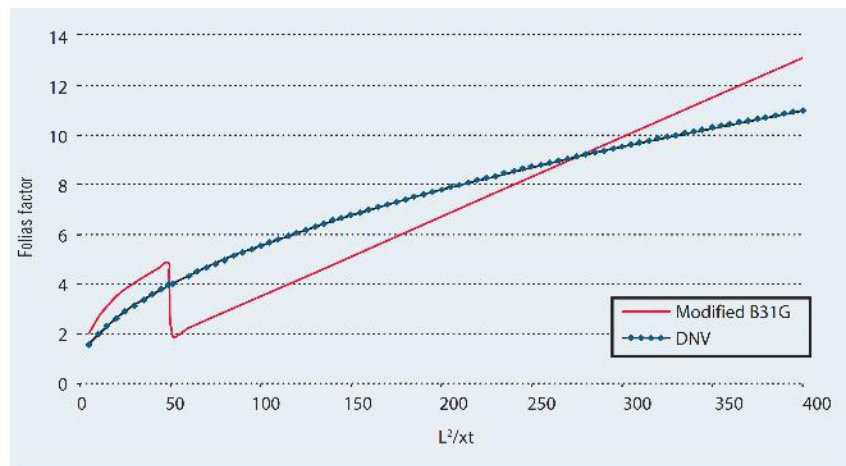


FIG. 1

Failure-stress assessment

A deterministic failure model generally uses recommendations of the various allowed standards to estimate failure stress according to geometrical dimensions of the defect using Equations 3 and 4³⁻⁴ and to plan the repair of corrosion defects using Equation 5. Dif-

GAS PIPELINE SPECIFICATIONS

OD	in.	42
Length	km	112
Flow rate	normal	
	cu m/hr	2,000,000
MAOP	barg	71.5

Table 1

EQUATIONS

$$x_{it} = x_0 + \mu_v \tau$$

Where:

x_{it} = estimated depth of defect, i, at the moment, τ

x_{in} = depth of defect, i, measured during the last inspection

μ_v = average corrosion growth rate, estimated by the following relation:

$$\mu_v = \frac{1}{N} \sum_{i=1}^N \frac{\Delta x_i}{\Delta \tau}$$

Where:

N = total number of detected defects

Δx_i = difference of the depths of the, i, defect metal loss between the two last inspections

$\Delta \tau$ = time interval separating the two last inspections

$$S_r = [S] \left[\frac{(1 - \gamma_r \cdot t)}{1 - M^{-1}(\gamma_r \cdot t)} \right]$$

Where:

$$[S] = f(\sigma_s, D, t)$$

$$S_r \leq \frac{P_{op} D}{2K_s t}$$

Where:

$[S]$ = allowable stress

t = pipe WT

γ_r = shape parameter (0.66 for a parabolic approximation of the defect, and 1 for a rectangular approximation)

x = defect depth

M = Folias factor

σ_s = specified minimum yield strength

D = pipeline OD

P_{op} = operating pressure

K_s = safety factor

$$P_r(\tau_i) = P(g(\tau_i) = X_{cr} - X(\tau_i) \leq 0) =$$

$$\int_{Z(\tau_i)}^{+\infty} f_x(x, \tau_i) dx + \int_{-\infty}^{Z(\tau_i)} f_{x_{cr}}(x) dx \quad (6)$$

(1) Where:

$Z(\tau_i)$ = the intersection between the load probabaility density functions and the resistance

$$x_{cr} = \frac{t}{\gamma_r} \left(\frac{[S] - P}{[S] - M^{-1}P} \right) \quad (7)$$

Where:

P = fluid pressure

$$f_{x_{cr}}(x) = \frac{1}{\sigma_{x_{cr}} \sqrt{2\pi}} \exp\left(-\frac{(x - \mu_{x_{cr}})^2}{2\sigma_{x_{cr}}^2}\right) \quad (8)$$

$$\sigma_v = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{\Delta x_i}{\Delta \tau} - \mu_v \right)^2} \quad (9)$$

$$f_{x(\tau)}(x) = \frac{1}{\sigma_x(\tau) \sqrt{2\pi}} \exp\left(-\frac{(x - \mu_x(\tau))^2}{2\sigma_x^2(\tau)}\right) \quad (10)$$

Where:

$$\mu_x(\tau) = x_0 + \mu_v \tau \quad (11)$$

$$\sigma_x^2(\tau) = \sigma_x^2 + \sigma_v^2 \tau^2 \quad (12)$$

$$\int_{-\infty}^x f_{x_{cr}}(x) dx = F_{x_{cr}}(x) = \Phi\left\{ \frac{Z(\tau) - \mu_{x_{cr}}}{\sigma_{x_{cr}}} \right\} \quad (13)$$

$$\int_{Z(\tau_i)}^{+\infty} f_{x(\tau)}(x) dx = \bar{F}_{x(\tau)}(x) = 1 - \Phi\left\{ \frac{Z(\tau) - \mu_{x(\tau)}}{\sigma_{x(\tau)}} \right\} \quad (14)$$

Where:

Φ = the cumulative function of standard normal distribution.

$$P_r = \bar{F}_{x(\tau)}(x) + F_{x_{cr}}(x) \quad (15)$$

$$sP_{Ji}(\tau) = 1 - \prod_{i=1}^{N_J} (1 - P_{Ji}(\tau)) \quad (16)$$

Where:

P_{Ji} = failure probability of the i^{th} corrosion defect of the J^{th} kilometer at time, τ

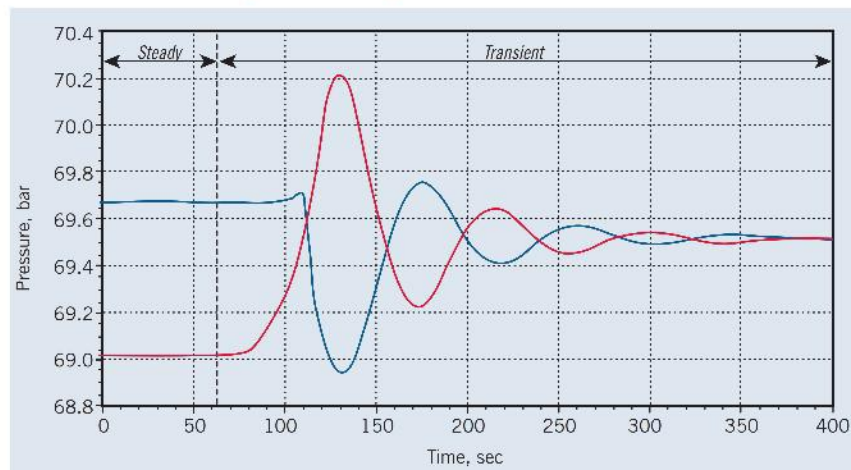
N_J = total number of corrosion defects detected in the pipeline section corresponding to the J^{th} km

ferences in the recommendations of the various standards lie in their expression of the Folias factor, which modified standard ASME B31G calculates differently according to whether the corrosion defect type is pinhole or crater (Fig. 1).

This approach, however, involves uncertainties. Despite significant progresses in ILI-tool design, uncertainty on measures of defect depths remains at about 10% of WT for a confidence level of 80%, suggesting a potential risk of

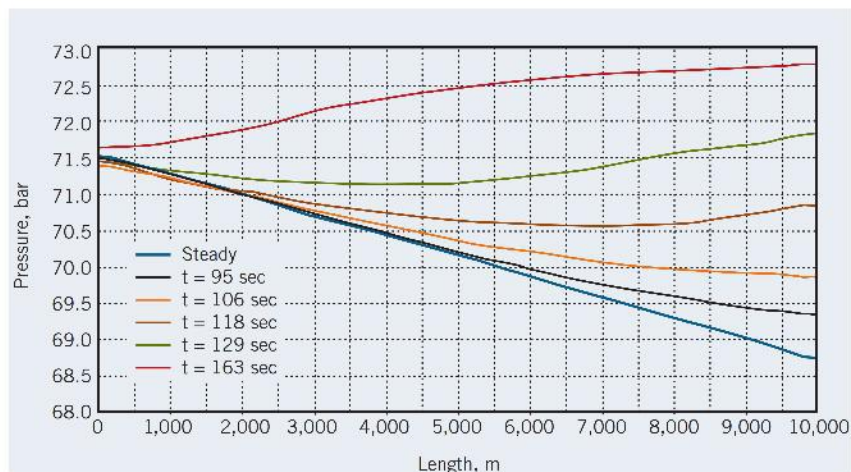
PRESSURE EVOLUTION, SECTION 1, POST-VALVE CLOSE

FIG. 2



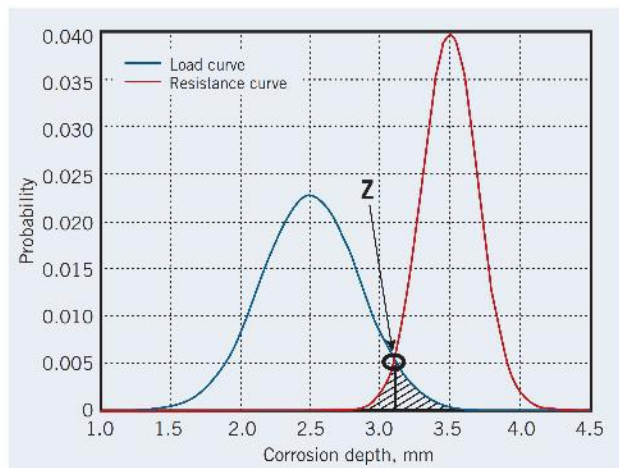
PIPELINE PRESSURE EVOLUTION, POST-VALVE CLOSE

FIG. 3



FAILURE AREA

FIG. 4



over- or underestimating failure stress. Specified mechanical properties of the steel grade correspond to minimal requirements of acceptance or refusal of the pipe during manufacture, resulting in yield strength generally much higher than specified values and implying that pipe resistance is generally underestimated.

Corrosion is a complex process and its evolution, from one corrosion defect to another, is not uniform, depending on many factors including coating state, soil aggressiveness, and cathodic protection efficiency. Operating pressure varies depending on scheduled flow rates and particularly overpressures generated in transient and surge situations (Fig. 2).

It is therefore necessary to implement an approach allowing for:

- Uncertainties in measurement generated by the inspection tool, by the mechanical properties of steel, and by the corrosion growth rate.
- Quantitative estimation of the failure probability associated with a given corrosion state established on results of the last inspection.
- Evaluation of the remaining probability of failure after repair of critical defects.
- Influence of overpressures caused by transient and surge situations.

Transient flow

During project phase, transient and surge analyses check the resistance of the pipeline. The new pipe is considered devoid of corrosion defects. Transient and surge situations occur when fluid flow velocity changes abruptly because of a valve closure or other status change in a control component, causing a pressure wave that moves from one point to another at the sound speed inside the fluid. The wave therefore potentially subjects the pipe to pressure values exceeding the limits of pipeline resistance (Fig. 3).

Many leaks and explosions in Niger delta pipelines are attributable to a conjunction of corrosion state surge-generated overpressures.³ This article, however, is restricted to presenting a procedure defining the maximum steady-state operating pressure needed to ensure excessive transient pressures don't exceed the resistance limits of corroded pipe, using DNV-F101.

As part of preliminary planning for a project to increase flow rate of a pipeline in Brazil, engineers proposed analyz-

ing the integrity of the system using the transient simulation software STONER and a deterministic model to estimate failure stress.⁶ Analyzing the transient regimes in pipelines mathematically requires solving a system of partial differential equations subjected to initial and boundary conditions characterizing the studied case.

The mathematical difficulties inherent in the resolution of such systems prompted development of powerful dynamic simulators, which can deal with all the possible configurations. This article uses SIMONE 5.66 dynamic simulation software for gas pipelines networks.

Probabilistic analysis

Variability in the corrosion growth rate and uncertainties regarding resistance limits, tool accuracy, and pipeline geometry, have prompted some to use probabilistic approaches instead of deterministic approaches.⁷ Since evolution of the degradation processes over time is uncertain, these can best be represented by stochastic processes (OGJ, Oct. 1, 2012, p. 122; Nov. 5, 2012, p. 132).

Probabilistic structural analysis forms a mathematical model through which it is possible to calculate the probability that a structure is found in a specified state, knowing both that one or more of its properties are random and that loads on the structure are also random. Parity between the load and resistance defines the limit state. When load becomes greater than resistance, failure occurs.

In the case of corroded pipeline the dimensions of metal loss are load conditions and the allowable dimensions of the defect resistance conditions.^{8,9} Failure occurs when corrosion depth, x , reaches critical depth, x_{cr} . Failure probability corresponds to the surface represented by the shaded area in Fig. 4.

The dynamic nature of degradation processes therefore makes the load a function of time, τ , tending to increase when resistance is constant (Equation 6).

Resistance-curve modeling

If the main dimension characterizing the default risk is represented by the depth of corrosion, then rearranging Equation 3 yields the critical depth of corrosion expressed in Equation 7. Considering a normal distribution with known average and variance, yield strength's uncer-

LOAD-FUNCTION EVOLUTION

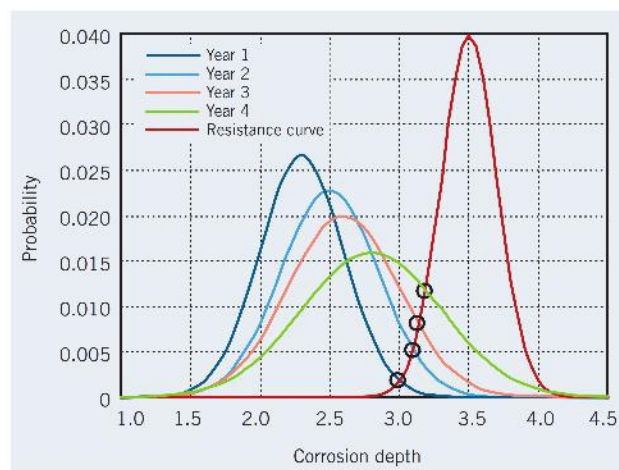


FIG. 5

PIPELINE CORROSION, SECOND INSPECTION

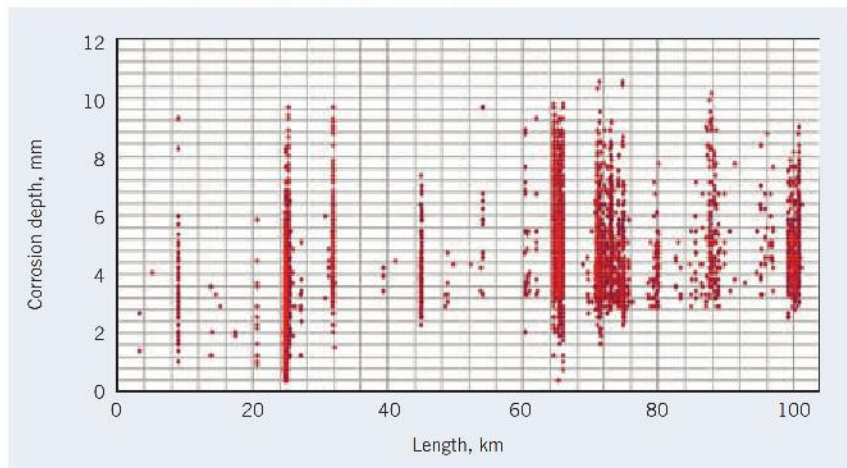


FIG. 6

PIPELINE CONFIGURATION

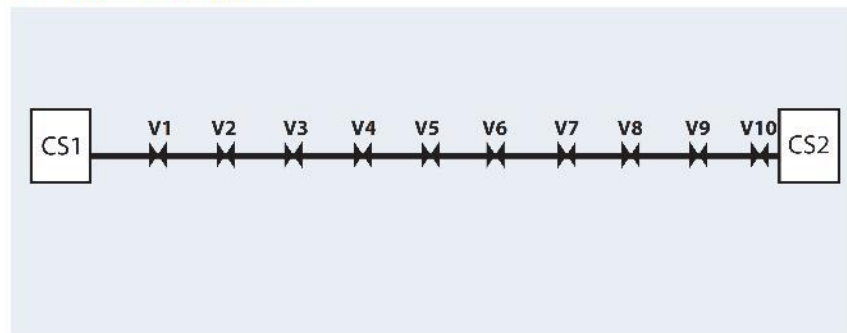
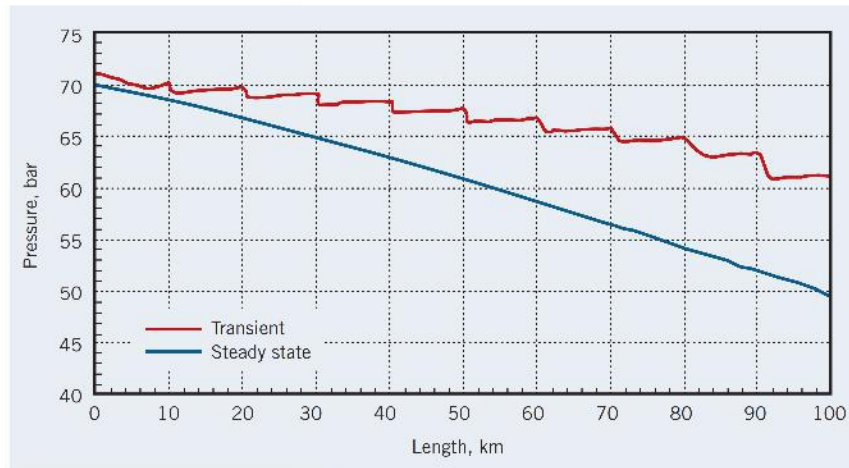


FIG. 7

tainy in Equation 4 is described by determining moments $\mu_{x_{cr}}$ and $\sigma_{x_{cr}}$ of X_{cr} distribution on the basis of Monte Carlo simulation, yielding the resistance curve expressed by Equation 8.

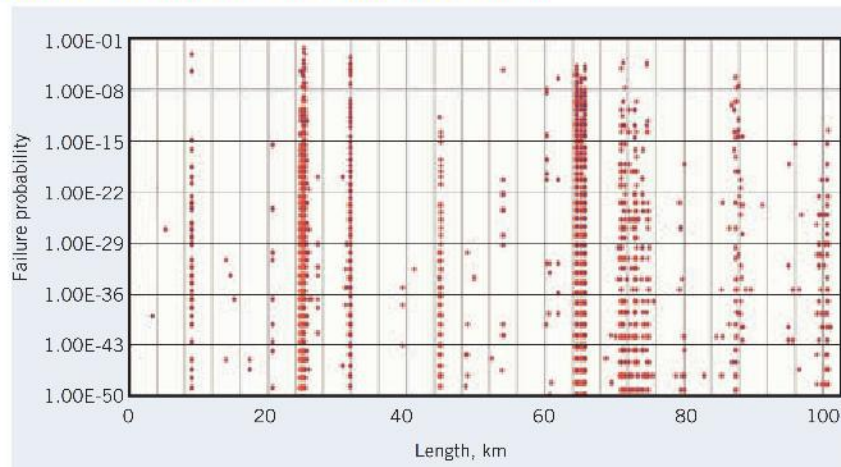
STEADY-STATE PRESSURE, TRANSIENT MAXIMUM

FIG. 8



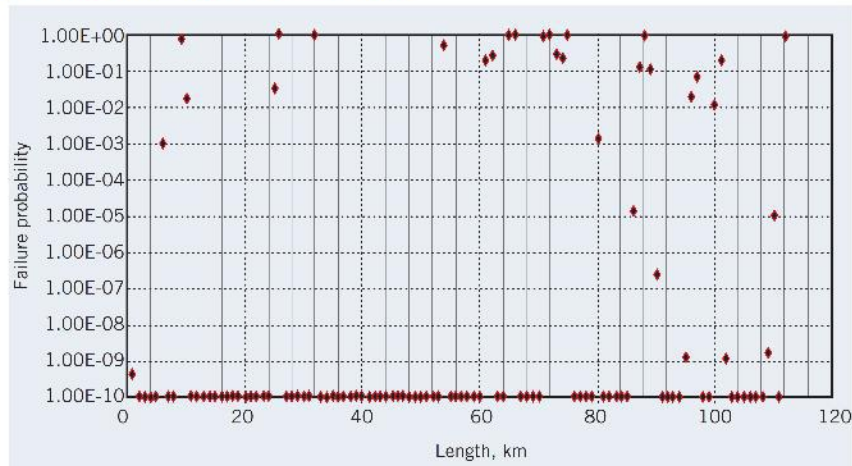
FAILURE PROBABILITY PER CORROSION DEFECT

FIG. 9



FAILURE PROBABILITY, PRE-REPAIR

FIG. 10



Load curves

Measuring evolution of metal-loss depth guides estimation of corrosion growth rates. In a corroded pipeline, each pipe element can contain hundreds or even thousands of corrosion points of various sizes. Assuming normal distribution and the requirement of a minimum of two inspections, classical statistical treatment can generate corrosion growth rate distributions. Equation 2 calculates the average, μ_c , while Equation 9 estimates standard deviation.

Assuming a linear process of corrosion, Equations 10-12 describe the evolution of the load curve over time.

The equalization of load distributions and resistance defines the intersection coordinates of $Z(\tau)$ (Fig. 5). Calculation of failure probability uses Equation 6, with the surface of failure between the resistance curve and the intersection point obtained by integrating the curve of resistance (Equation 13). Integrating the load curve obtains the part of the surface of failure ranging between the intersection point and the load curve (Equation 14).

Adding the two surfaces determines the probability of failure (Equation 15).

Failure probability

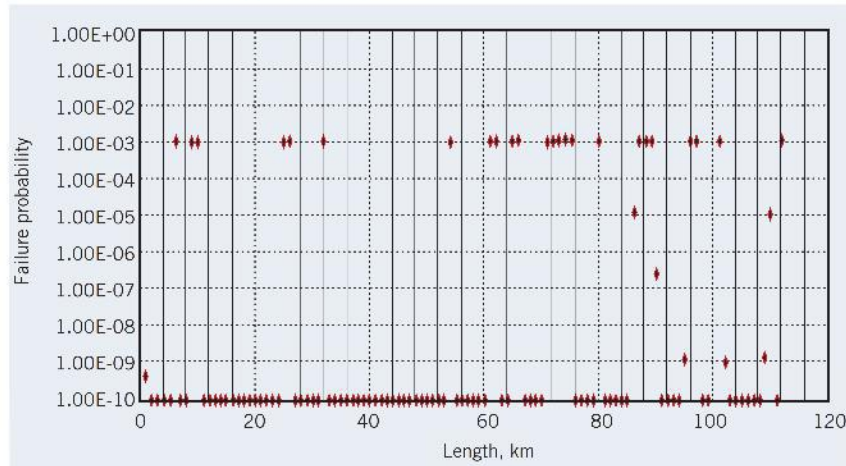
A repair program follows ILI inspection. Simulating failure probability before and after repair and comparing results to a threshold criterion adopted by the operator can provide for optimal planning of preventive repairs. The threshold value used in worldwide practice refers to failure probability/kilometer.¹ In a corroded pipeline, each kilometer can contain several corrosion defects of various dimensions (Fig. 6).

Following reliability theory and assuming that corrosion defects are independent elements installed in series,^{10, 11} the probability of failure at the moment, τ , of the pipeline section corresponding to the J^{th} km is expressed by Equation 16.

The repair program can use the es-

FAILURE PROBABILITY, POST-REPAIR

FIG. 11



INSPECTION RESULTS

Table 2

	Inspection 1	Inspection 2	Matched defects
Inspection tool	MFL	MFL	—
Number of corrosion points found	4,294	5,307	940
Corrosion quality	External	External	—

estimated failure probability as its basis, determined in Equation 16 by assigning a value of zero probability for each corrosion defect to be repaired. This approach allows hierarchical optimal planning of repairs to maintain a failure probability below risk tolerance, followed by scheduling inspection with intelligent tools.

It follows from the assumption that corrosion defects are independent elements that the failure probability of a section of pipeline must be determined starting from the probabili-

ties of failure of all the corrosion defects present on this section.

A section of pipeline with a great number of defects of average size could prove, in certain cases, more dangerous than a section exhibiting a reduced number of points of corrosion of more significant size. This perspective is cut off from view by interposed matter in practice when analysis is performed defect by defect.

A section of Algerian gas pipeline between two compressor stations (Fig. 7), with parameters shown in Table 1, was inspected twice (Table 2). Simulating the closing of the successive valves in 60-sec intervals (Fig. 8) defined the envelope of maximum transient pressure. The model described in this work allowed computation of the failure probability per corrosion defect along the pipeline (Fig. 9) and the failure probability/kilometer before repair (Fig. 10).

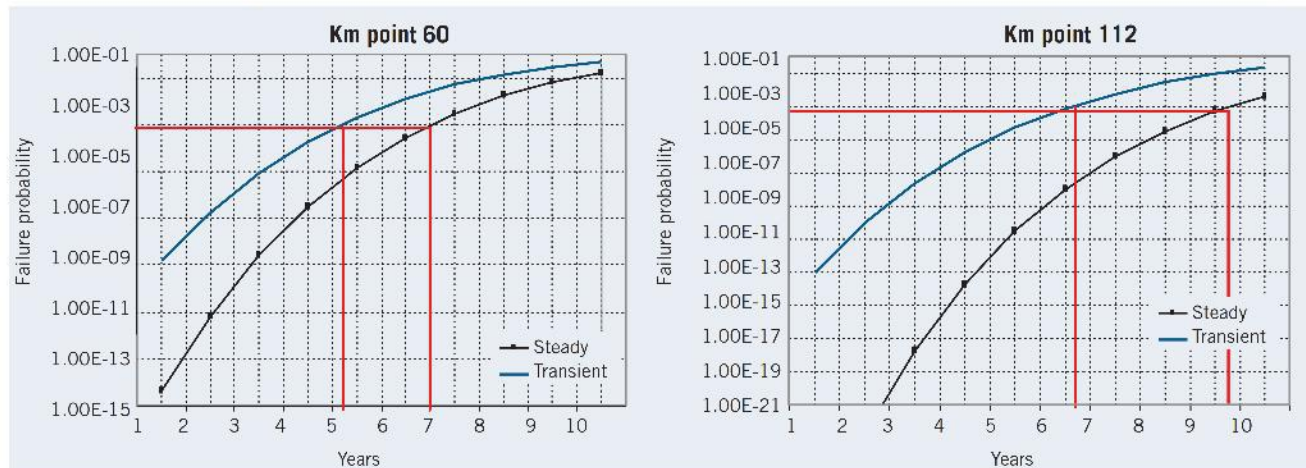
Applying Equation 16 and the 10^{-3} threshold criterion allowed identification of the corrosion defects to be repaired and computation of the failure probability/kilometer after repairs (Fig. 11). Only the failure probability of crater-type corrosion defects differs significantly between using steady and transient approaches (Fig. 12), with the failure probability of pinhole defects remaining practically the same (Fig. 13). **OGJ**

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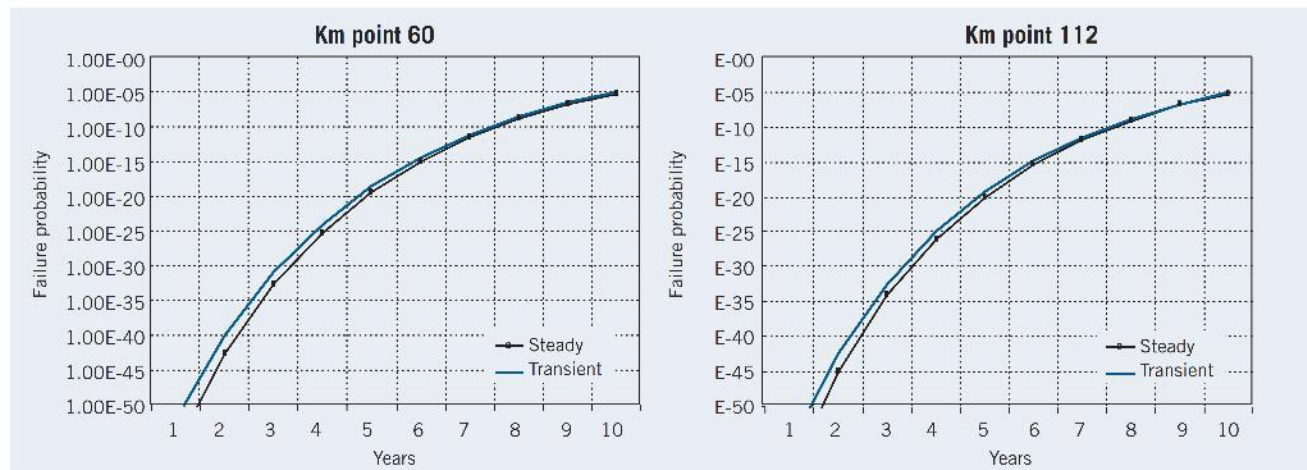
FAILURE PROBABILITY, CORROSION CRATER

FIG. 12



FAILURE PROBABILITY, PINHOLE CORROSION

FIG. 13



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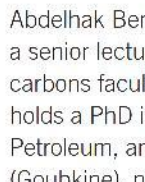
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