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# Identification of failure type in corroded pipelines: A Bayesian probabilistic approach

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ABSTRACT

Spillover of hazardous materials from transport pipelines can lead to catastrophic events with serious and dangerous environmental impact, potential fire events and human fatalities. The problem is more serious for large pipelines when the construction material is under environmental corrosion conditions, as in the petroleum and gas industries. In this way, predictive models can provide a suitable framework for risk evaluation, maintenance policies and substitution procedure design that should be oriented to reduce increased hazards. This work proposes a Bayesian probabilistic approach to identify and predict the type of failure (leakage or rupture) for steel pipelines under realistic corroding conditions. In the first step of the modeling process, the mechanical performance of the pipe is considered for establishing conditions under which either leakage or rupture failure can occur. In the second step, experimental burst tests are used to introduce a mean probabilistic boundary defining a region where the type of failure is uncertain. In the boundary vicinity, the failure discrimination is carried out with a probabilistic model where the events are considered as random variables. In turn, the model parameters are estimated with available experimental data and contrasted with a real catastrophic event, showing good discrimination capacity. The results are discussed in terms of policies oriented to inspection and maintenance of large-size pipelines in the oil and gas industry.



## 1. Introduction

The crude oil and gas industry produces massive amounts of hazardous chemicals products that are transported to transformation and consumption centers by intricate pipeline networks. Nominally, the material used for pipeline construction is designed to operate under severe stress conditions. For instance, the strength capacity of the pipeline materials is about 150% higher than the specified minimum yield stress (SMYS). The pipelines used to transport liquid material are subjected to pressures of the order of 40% of the SMYS, while those used for gas products are operated under 70% of SMYS. This means that the mechanical performance of the pipelines should be located within the elastic range. While pipelines are designed and constructed to maintain their integrity, diverse factors (e.g., corrosion) make difficult to avoid the occurrence of leakage in a pipeline system during its lifetime. In fact, the strength capacity of the construction material suffers a continuous deterioration induced by unavoidable corrosion phenomena present along thousands of kilometers of changing environments. Consequently, pipelines can achieve limiting stress conditions and failures, including leakage and even rupturing with severe spillover, could occur in the neighborhood of populated area [1]. In this way, the design of optimal inspection, maintenance and substitution policies should consider the complex effects of corrosion in the operation of pipelines transporting hazardous material.

A visual inspection of corrosion damage in pipelines can show the reduction of material on the surface. That is, the damaged region by corrosion effects suffers the reduction of pipe wall thickness and, hence, the decrement of the strength capacity expressed in term of the pressure stresses. Given the potential disastrous effects of a pipeline rupture for the crude oil industry and threaten for the population in a neighborhood of a pipe; it is of prime importance to dispose of simple and effective procedures to evaluate risk failure. In the recent decades, some effort has devoted to the understanding and modeling of the mechanisms leading to pipeline failure [2,3]. Several studies have been oriented to quantify the operation limits of pipelines under realistic conditions [4–21]. Research efforts have been oriented to numerical and mathematical modeling by means of finite-element techniques, as well as to the design of experimental burst tests for understanding the pipeline performance under

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degradation process. Actual numerical modeling and experimental techniques have been refined so that accurate prediction of the failure pressure for corroded pipelines is possible [14,20,22]. Despite these research efforts, a problem that still lacks response is the type of failure (either leakage of rupture) that can appear in a damaged pipeline zone. Results focusing on this issue classify the failure into two main types; namely, leakage and rupture [7,8,12,16]. Strictly, a failure occurs when the internal pressure exceeds the material resistance. In other words, a failure is found when the hoop stress is larger than the limiting material stress (plastic collapse), provoking the generation and propagation of fractures on the pipe wall thickness. A failure is of the leakage type if the fractures are not propagated in the axial direction. In contrast, a failure is of rupture type if the fractures are extensively propagated along the axial direction, indicating that the strength to the fracture propagation is largely exceeded [16]. In a seminal paper, Shannon [7] proposed a semi-empirical criterion, based on two limiting state functions, to discriminate between the two failure types. The first function was used to separate the no-failure region from the leakage or plastic failure. The second function was intended to separate the regions corresponding to leakage and rupture failures. Experimental and field data have shown that the Shannon's criterion is conservative in the sense that a significant amount of leakage failures are identified as fracture failures.

The identification of the type of failure is a problem of prime importance for maintenance and emergence purposes. In general, social, environmental and economical impacts of pipeline failures are more important for rupture than for leakage. Although it is clear that avoiding failures is a central task, the design, inspection and maintenance norms establish structural safety thresholds. It is apparent that, given the corroding conditions of real pipelines, the occurrence of failures is unavoidable. However, from economical and environmental standpoints, is highly desirable to reduce the occurrence of failures to that of the leakage type. In this way, the design of maintenance and inspection procedures should be based on an accurate quantification of the occurrence of the type of failure in order to reduce the adverse effects of ruptures with potential negative effects.

Ideally, the study of pipeline failure should be started with a complete understanding of the propagation of fractures in damaged material. However, fracture dynamics display complex and highly unpredictable behavior, so its quantitative characterization for prediction purposes is unrealistic from a practical standpoint. For instance, the size and depth of damage for corroded pipes are hardly measured. Fortunately, experimental evidence [7,16] has shown that the type of failure is strongly correlated to the extent of the corrosion damage. Motivated by this, the present work proposes a Bayesian probabilistic approach to identify and predict the type of failure (leakage or rupture) for steel pipelines under realistic corroding conditions. In a first step of the modeling process, the mechanical performance of the pipeline is considered to establish conditions under which either a leakage or rupture failure occur very high probabilities. In a second step, experimental burst tests are used to introduce a mean probabilistic boundary defining a region where the type of failure is uncertain. In the boundary vicinity, the failure discrimination is carried out with a probabilistic model where the events are considered as random variables. In turn, the model parameters are estimated with available experimental data and contrasted with a real catastrophic event, showing good discrimination capacity.

## 2. Shannon's modeling approach

As a preliminary step towards the description of the Bayesian approach proposed in this paper, the basic concepts introduced by Shannon in his seminal work [7] on the failure behavior of line pipe defects, are described in this section. In Shannon's approach, the mechanical characteristics defining failure and non-failure conditions as well as the leakage and breakage boundaries are identified in terms of explicit equations describing the pipe stress conditions. In this way, for the sake of completeness, a brief review of the deterministic behavior of pipe defects is described as follows.

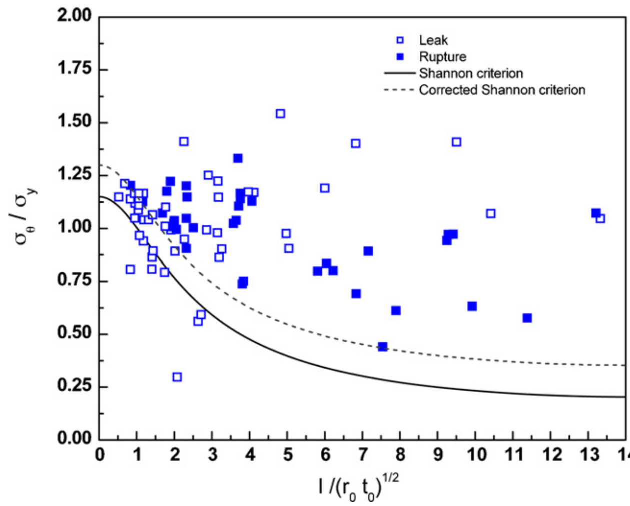


**Fig. 1.** Leak-rupture behavior of pipeline defects according to Shannon model.

The underlying assumption behind Shannon's work is that a failure shall occur in a duct if the hoop stress $\sigma_\theta$ is smaller than the yield stress $\sigma_Y$, multiplied by the damage factor $\zeta$; that is, a failure occurs with probability one if $\sigma_\theta < \zeta\sigma_Y$. In contrast, a failure will surely occur in a pipe with corrosion damage if $\sigma_\theta \geq \zeta\sigma_Y$. The damage factor $\zeta \leq 1.15$ is defined as follows:

$$\zeta = 1.15\left[\frac{A_0 - A}{A_0 - AM^{-1}}\right] \quad (1)$$

where $A_0 = l_0 t_0$ is the area of the pipe wall associated to the damage axial length $l_0$ and the original (*i.e.*, without damage) wall thickness $t_0$. In addition, $A$ is the area of damaged surface in the axial direction and $M$ is a parameter known as the Folias factor [3], which is a function of $l_0$, $t_0$ and the interior pipe radius $r_0$; namely,

$$M = \left[1 + 1.255\frac{(l/2)^2}{r_0 t_0} - 0.0135\frac{(l/2)^2}{r_0^2 t_0^2}\right] \quad (2)$$

On the other hand, leakage and breakage failures shall occur if $\sigma_\theta < 1.15M^{-1}\sigma_Y$ and $\sigma_\theta \geq 1.15M^{-1}\sigma_Y$, respectively. In this way, $\sigma_\theta - 1.15M^{-1}\sigma_Y = 0$ defines a failure-type boundary (see Fig. 1). The region located above the boundary corresponds to ruptures, while the region below the boundary to leakages. Fig. 1 also shows the experimental results for both leakage and rupture failures according to the experimental conditions reported in [8,12] for pipelines with steel grades from API 5L X42 to API 5L X65, and external diameter from 32 to 914 mm, and wall thickness from 6 mm to 11 mm. From 86 pipelines with corrosion damage, 52 showed leakage failure while 34 presented rupture problems.

The Shannon's approach is deterministic in nature, and so it may lead to incomplete discrimination of the failure type. In fact, for normalized length $l/\sqrt{r_0 t_0}$ in the range (0,2), a significant test fraction are wrongly classified in the sense that the failure was of leakage type and the Shannon's model predicts a rupture failure. In this way, the applicability of the Shannon's model is limited to values of $l/\sqrt{r_0 t_0}$ smaller than 2.0. As a tailored way for fixing this problem, a factor 0.15 was incorporated, such that the boundary is now defined by $\sigma_\theta/\sigma_Y = 1.15M^{-1}\sigma_Y + 0.15$. This boundary is displayed in Fig. 1 as a dotted line, showing an improvement in the prediction performance. Besides its heuristic origin, a drawback of this approach is that conservative results can be obtained as the factor 0.15 was introduced from the knowledge of an unavoidable limited number of experimental cases. In fact, a significant fraction of the experimental tests failed in leakage mode while the model predicts rupture failure. As shown by Fig. 1, acceptable prediction is obtained for stress conditions in the range $\sigma_\theta/\sigma_Y < 0.7$. As expected, the monotonous decreasing form of the limiting function obeys to the fact that the hoop stress for small scales is larger than those for larger scales. From a descriptive viewpoint, this means that the larger the damage, the higher the failure likelihood. However, for very large damages, the failure can be of the rupture type. On the contrary, leakage failure occurs, in general, for small damage.

It can be observed in Fig. 1 the large amount of large pipelines that had a leakage failure, for which the hoop stress is about 1.5 times the yield stress. This can be explained because the depth of corrosion damage is small, which was not considered by the Shannon's model. In this way, a more complete modeling of pipeline failures should also consider the corrosion damage degree (*e.g.*, length and depth). In fact, the type of failure is linked to the amount and geometry of damaged surface. For instance, gas and liquids pipelines have relatively small wall thickness, so that the labile surface depends more on the length of the damage rather than on the depth of the corrosion effect.

According to the theory of fracture mechanics [22], the prediction of fracture propagation in a pressurized pipeline requires the knowledge of the material toughness and the geometry of the fracture. Unfortunately, given the large amount of events affecting the evolution of materials in realistic conditions, these parameters are hardly measured or estimated. In actual situations, only a constitutive function of the material and an estimation of the damaged region size are known. In the following sections, the problem of estimating the failure type in terms of available experimental and/or field measurements is addressing by using a probabilistic modeling framework.

## 3. The space of the stress-mechanical properties

In this section, we reformulate the Shannon's approach for the discrimination of failure type in terms bounds of stress-mechanical properties under corrosion conditions. It is clear that the resistant pressure $p_R$ for a pipe with corrosion damage cannot be larger than the nominal corresponding resistant pressure. That is, corrosion defects always lead to a degradation of the material performance. Experimental evidence [11,12] and numerical simulations with finite-elements [13,21] have shown that the resistant pressure for a pipe with corrosion damage is always larger than the resistant pressure for an infinitely large groove with a maximum damage depth equal to that of the corrosion defect. According with this, the resistant pressure for a pipe with corrosion damage satisfies $p_{\mathrm{LongGroove}} \le p_R \le p_{\mathrm{Plain}}$, where $p_{\mathrm{Plain}}$ is the nominal (i.e., without corrosion effects) resistant pressure and $p_{\mathrm{LongGroove}}$ is the resistant pressure for an infinite longitudinal groove of a given depth. Bony et al. [21] showed that the fault resistant pressure $p_R$ meets the proportionality $p_R \propto t_{ER}/r_0$, where $r_0$ is the interior pipe radius and $t_{ER}$ is the equivalent wall thickness given by

$$t_{ER} = t_0 - d_{\max}(1 - g_d^{\min}) \tag{3}$$

here $t_0$ is the physical wall thickness, $d_{\max}$ is the maximum damage depth and $g_d^{\min} = \min\{g_d(x_0)\}$ is a correction factor taking values into the interval [0,1] and depends of the corrosion damage geometry along the longitudinal direction. This factor quantifies the contribution of the remnant material to the resistant pressure. The failure pressure is associated to the minimum value of the function $g_d(\cdot)$ resulting of evaluating this function at each point $x_0$. As illustrated in Fig. 2, the failure point $x_0$ is located within the coordinates $\hat{a} = x_1$ and $\hat{b} = x_n$ defining the damage boundaries. An appropriate Cartesian system is used for describing the damage geometry where the damage depth is defined on one of the coordinate's axis. Following the computations made by Oliveros et al. [18], the function $g_d(\cdot)$ is defined as follows:

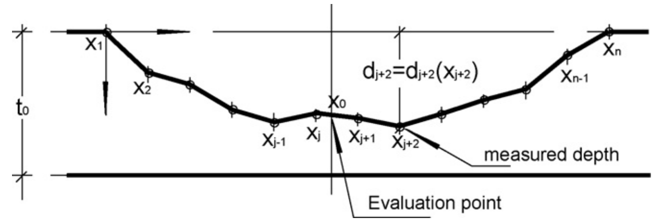


**Fig. 2.** Irregular geometry of a corrosion damage in discretized points.

$$g_d(x_0) = 1 - \frac{\beta}{\pi d_{\max}} \int_{\hat{a}}^{\hat{b}} \sec h(\beta(x_0 - x))\, d(x)\, dx \tag{4}$$

where $\sec h(\cdot)$ is the hyperbolic secant, $\beta = (D(t_0 - d_{\max}))^{-1/2}$ and $D = 2(r_0 + t_0)$. It is noted that $d_{\max} = 0$ for a damage-free pipe; hence, the equivalent thickness is equal to the nominal wall thickness and the resistant or failure pressure is obtained as $p_R = p_{\mathrm{Plain}} \propto t_0/r_0$ [21]. In this way, if the defect is an infinitely large groove of with depth $d_{\max} \neq 0$, then $g_d^{\min} = 0$, $t_{ER} = t_0 - d_{\max}$ and the resistant pressure is obtained as $p_R = p_{\mathrm{LongGroove}} \propto (t_0 - d_{\max})/r_0$. Fig. 3 shows the factor $g_d^{\min}$ as a function of the normalized damage length $l/D$ and depth $d_{\max}/t_0$. It is noted that $g_d^{\min}$ decreases exponentially with respect to the damage length, meaning that the failure risk increases exponentially with the advance of the corrosion size.

Fig. 1 shows that a rupture failure is most likely for large damage lengths. On the other hand, leakage can occur mostly for relatively small damage lengths. As discussed above, the type of failure is associated to the damage extent. Accordingly, one can define a bounded stress space as

$$\frac{p_R}{p_{\mathrm{Plain}}} = 1 - \frac{d_{\max}}{t_0}(1 - g_d^{\min}) \tag{5}$$

It is noted that this ratio takes values within the unit interval and varies linearly as a function of $g_d^{\min}$. Fig. 4 shows that the bounded stress space as given by Eq. (5) is triangular and is specified in terms of stress values and the damage geometry. It should

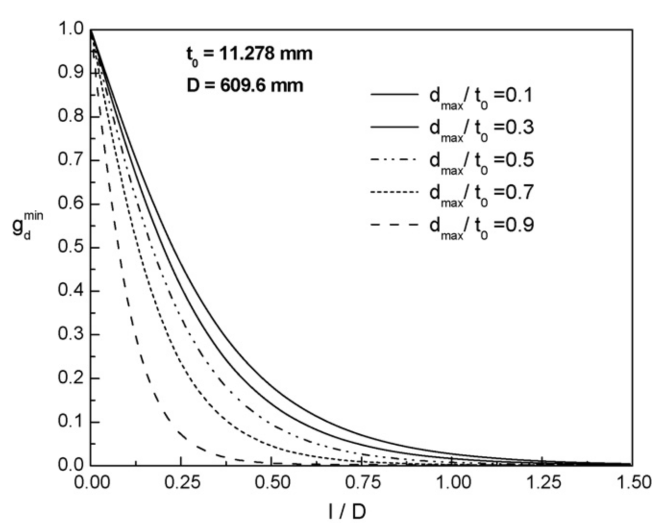


**Fig. 3.** Parameter $g_d^{\min}$ for a defect with parabolic geometry as a function of its maximum depth and length.

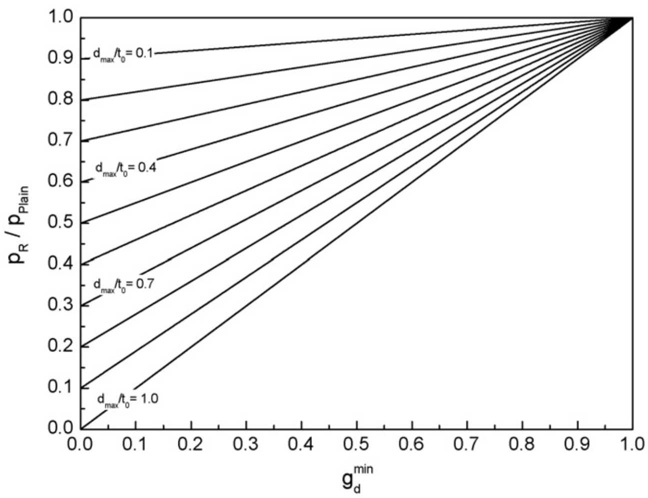


**Fig. 4.** Space of normalized stresses and pipeline mechanical properties.

be noted that $g_d^{min}$ is an index of the damage geometry. If the damage defect is flat, such that $d(x) - d_{max} = 0$, then the defect should yield an infinitely large groove as $l \to 2r_0$. In this case, $g_d^{min} \to 0$. In contrast, as the damage advances in the sense that $d(x) - d_{max} \gg 0$, the index $g_d^{min} \to 1$.

Fig. 5 compares the experimental tests from [8,14] with the prediction made by Eq. (5). Pipelines that showed a rupture type failure had pressure relations higher than those ducts that had a leakage type failure. It is observed that the boundary between leakage and rupture failures is non-lineal as a function of $g_d^{min}$. However, several experimental tests do not follow this trend, which indicates that many other factors affect the type of failure. In general, these factors should also depend on the complex nature of the defect or damage geometry. For instance, establishing a maximum depth as in Fig. 2 is not an easy task given that many local maximums can be expect around a damaged region by corrosion effects. To address this problem, the modeling approach based on mechanical-stress properties will be posed within a probabilistic framework to account for uncertainties in the different corrosion parameters.

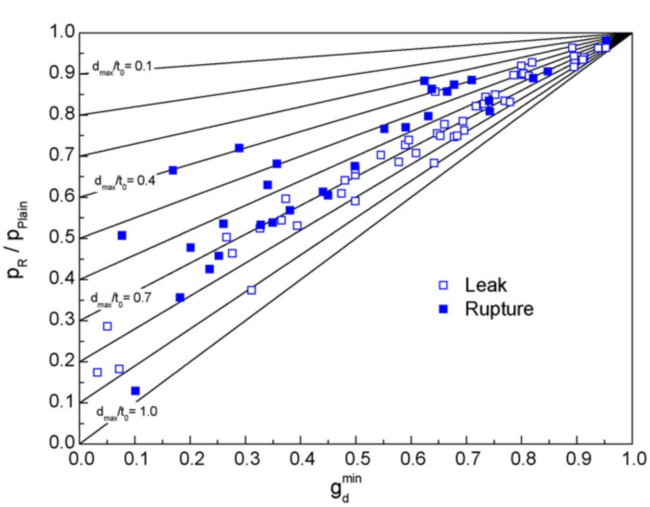


**Fig. 5.** Leak-rupture data in normalized stress-mechanical properties space. Note that the discrimination of these events is not clearly established from a direct visual inspection of the data.

### 3.1. A probabilistic model for failure-type discrimination

The research work following the deterministic Shannon's approach assumed the existence of a well-defined boundary separating the failure type. In turn, such boundary was given in the above section as a limiting state function (Eq. (5)) contained into the triangular region defined by $p_R/p_{Plain}$ and $g_d^{min}$. As observed in Fig. 5, the Shannon's boundary provides accurate discrimination only for extreme failures. However, many failures that cannot be discriminated are concentrated in the vicinity of the boundary. This suggests that these failures are affected by uncertainties that cannot be described within a mechanical model. It is apparent that uncertainties are of random nature, which limits the ability of simple and deterministic stress balance modeling to predict the type of failure. In the following, we shall introduce a more systematic approach by considering the random nature of uncertainties.

The variability associated to the pressure in a pipe with corrosion damage can be represented by means of the random variable $P_R = \xi_R p_R$, where $\xi_R$ is a random variable with unit mean and variation coefficient equal to $V_R = 0.13$, and $p_R$ is the failure pressure predicted with the Bony et al.'s [21] deterministic approach. In the same way, the pressure for a damage-free duct can be represented as $P_{Plain} = \xi_{Plain} p_{Plain}$, where $\xi_{Plain}$ is a unit variation random variable with variation coefficient equal to $V_{Plain} = 0.04$, and $p_{Plain}$ is the deterministic plain pressure. Given that $p_R$ and $p_{Plain}$ are random variables, the ratio $\nu = p_R/p_{Plain}$ is also a random variable that can be expressed as $\nu = \xi_\nu \nu_0$, where $\nu_0 = p_R/p_{Plain}$ is the deterministic ratio while $\xi_\nu = \xi_R/\xi_{Plain}$. According with standard probability theory [23], the random variable $\xi_\nu$ has unit mean and variation coefficient $V_\nu$ given by

$$V_\nu^2 = \frac{V_R^2 - V_{Plain}^2}{1 + V_{Plain}^2} = 0.0153, \quad V_R > V_{Plain} \tag{6}$$

Fig. 5 shows that the prediction of the failure type for damaged pipelines with values of $\nu$ close to the Shannon's boundary is more uncertain than for those far from the boundary. It is apparent that the deterministic boundary separating the failure type has an exponential form, suggesting that one can represent such boundary as a power-law function of the form $(g_d^{min})^{\beta''}$, where $\beta''$ is the estimated value of the random parameter $\beta$ in Eq. (4). According to this, a leakage should occur if and only if

$$W = (g_d^{min})^{\beta''} - \xi_\nu \nu_0 > 0 \tag{7}$$

and a rupture should occur when $W \le 0$. In this way, the probability that a pipe has a leak failure is obtained as follows:

$$P_L = P[W > 0] = \int_{W>0} f_{\xi_\nu}(x)\,dx = P\left[\xi_\nu \le \frac{(g_d^{min})^{\beta''}}{\nu_0}\right] \tag{8}$$

If one assumes that the random variables $\xi_R$ and $\xi_{Plain}$ are distributed as a log–normal function, the ratio $\xi_\nu = \xi_R/\xi_{Plain}$ is also log–normal distributed. According to this, Eq. (8) can be re-written as

$$P_L = \Phi\left[\frac{\beta'' \ \ln(g_d^{min}) - \ln \nu_0 + V_\nu^2/2}{V_\nu}\right] \tag{9}$$

where $\Phi$ is the accumulated normal PDF with zero mean and unit variance. Strictly, the leakage and rupture failure types are mutually exclusive and exhaustive events, meaning that the probability $P_R$ for a rupture failure is given by $P_R = 1 - P_L$. Hence, the probabilistic description of the random failure-type process should be approached with a simple Bernoulli process.

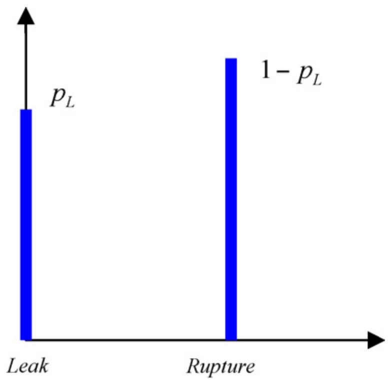


**Fig. 6.** Schematic Bernoulli probability model.

### 3.2. Bayesian estimation of $\beta''$

The failure probability given by Eq. (8) depends should be estimated in terms of experimental and field data. Commonly, accurate field data is hardly available, so that an optimal estimation strategy that exploits the data structure should be used. In this work, we propose a Bayesian approach for estimating parameters from a limited number of available data depending on mechanical and stress properties.

According to Eq. (9), it is sufficient to know the stress relationship $\nu=\nu_0$ and the damage region geometry characterized by $g_{\rm d}^{\min}$ to quantify the failure probabilities. In turn, these probabilities depend of the parameter $\beta''$, which should be estimated from real, experimental and field, data as those shown in Fig. 5. A procedure for estimating the parameter $\beta''$ can be described as follows. It is considered that the parameter $\beta$ is a random variable. From the Bayes Theorem, the *a posteriori* probability distribution function (PDF) $f''(\cdot)$ can be obtained from the empirical information obtained from $n$ experimental test in the following way:

$$f''(\beta\,|\tilde{x})=k_0\left\{\prod_{j=1}^{n}p_{R_j}^{Q_j}p_{L_j}^{1-Q_j}\right\}f'(\beta) \qquad (10)$$

where $f'(\cdot)$ is the a priori PDF, which provides initial information of the most likely values that a random variable. The simplest approach is to consider that the PDF is uniform in the unit interval and, in this work, the subinterval [0.4,0.8] is assumed. The product of probabilities in Eq. (10) is known as the likelihood function, which describes the joint probability for each individual failure type. The aim of the joint probability is to update the probabilities of the parameter $\beta$ as new experimental data is incorporated. The functions $p_{{\rm L}_j}=P_{\rm L}(g_{{\rm d}_j}^{\min},\nu_{0_j})$ and $p_{{\rm R}_j}=1-p_{{\rm L}_j}$ (see Fig. 6) describe respectively the probabilities of leakage and rupture of the $j$th experimental test with parameters $g_{{\rm d}_i}^{\min}$ and $\nu_{0_i}$, $j=1,\ldots,n$. In Eq. (10) the index $Q_j$ takes the value one if the $j$th experimental test failed by rupture. In the contrary case if the failure was leakage the index $Q_j$ takes the value zero. The value of the parameter $k_0$ is such that the area of the *a posteriori* PDF is equal to one. The statistical moments of the *a posteriori* PDF for the parameter $\beta$ are obtained as follows:

$$\beta''^{j}=\int_0^{\infty}z^j f''(z\,|\tilde{x})\,{\rm d}z \quad j=0,1,2,\ldots \qquad (11)$$

It can be shown that $k_0^{-1}=\beta''^{0}$, while the variance is given by $\beta''^{2}-(\beta'')^2$. It should be noted that the value $\beta''$ of the random variable $\beta$ corresponds to the expected value obtained from the Bayesian estimation.

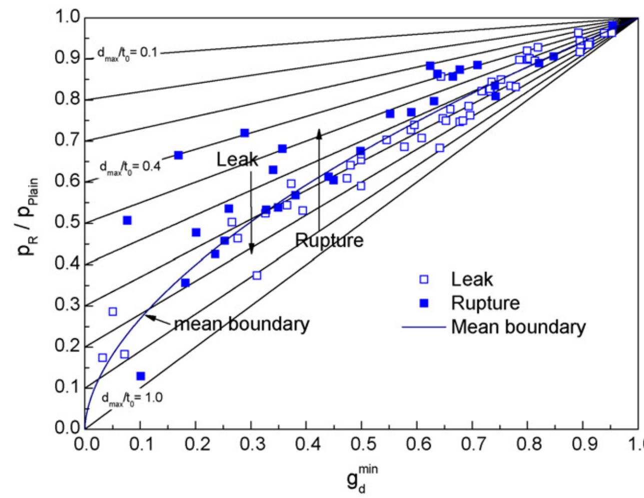


**Fig. 7.** Leak-rupture identification in normalized stress-mechanical properties space. Although most leak and rupture failure cases are discriminated by the Shannon model, several cases are not, suggesting the incorporation of additional discrimination variables.

## 4. Discussion

From the experimental tests shown in Fig. 5, Monte Carlo simulations provided the estimated value $\beta''=0.56$ with standard deviation equal to 0.02. The standard deviation-to-expected value is about 3.7%, indicating that 0.56 is a good estimate of the real value of $\beta''$. This also suggests that the parameter $\beta''$ can be also used within a deterministic framework to discriminate between leakage and rupture failures. Fig. 7 shows the boundary $(g_{\rm d}^{\min})^{\beta''}$ as a continuous line. The results of the experimental tests associated to the two failure types are mixed in a vicinity of the mean boundary given that for values $W=(g_{\rm d}^{\min})^{\beta''}-\xi_\nu\nu_0=0$, the rupture and leakage probabilities are equal. That is, the identification variability of a failure type is maximum around the boundary. For values $W\gg 0$ the probability for a duct to show a rupture failure increases significantly. In contrast, for values $W\ll 0$ the probability of a failure of the leakage type increases at the expenses of a reduction of a rupture type failure. This is schematically illustrated in Fig. 7 by means of arrows indicating these directionalities. This is in agreement with experimental results showing that distinguishing type of failure is hardest as the parameters approach the mixing boundary.

Two cases were considered to test the ability of the Bayesian modeling framework to discriminate between the two failure types. In the first case, the model was calibrated against the field and experimental results reported by Leis and Forte [16] for steel pipe API 5L X52, with diameter 762 mm, and wall thickness 9.525 mm. These tests correspond to corrosion conditions leading to different damage depths. It should be remarked that these experimental test were not used for estimation of the parameter $\beta$, so it can be used to evaluate the predictive capability of the Bayesian probabilistic modeling framework. Fig. 8 shows the results, showing that the model leads to a good discrimination of the failure type. Only one of 12 tests was not discriminated, suggesting that the uncertainty associated to this test was excessively large. At least for this case, the method showed prediction effectiveness of the order of 93%.

A practical challenging case was also considered. The incident corresponds to the report NTSB/PAR-03/01 by the USA National Transport Safety Board. Briefly, at 5:26 a.m., mountain daylight time, on Saturday, August 19, 2000, a 30-inch-diameter natural gas transmission pipeline operated by El Paso Natural Gas Company ruptured adjacent to the Pecos River near Carlsbad, New

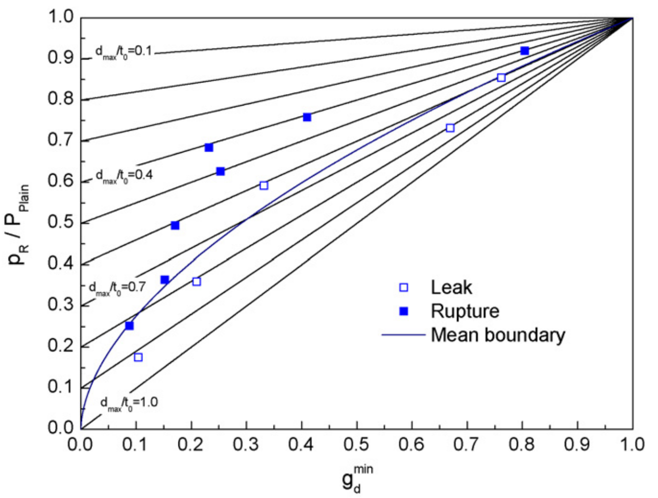


**Fig. 8.** Leak-rupture identification of Leis-Forte data in normalized stress-mechanical properties space. Open and filled square symbols correspond to leak and rupture, respectively. Except one boundary case, the model is able to discriminate between leak and rupture failures.

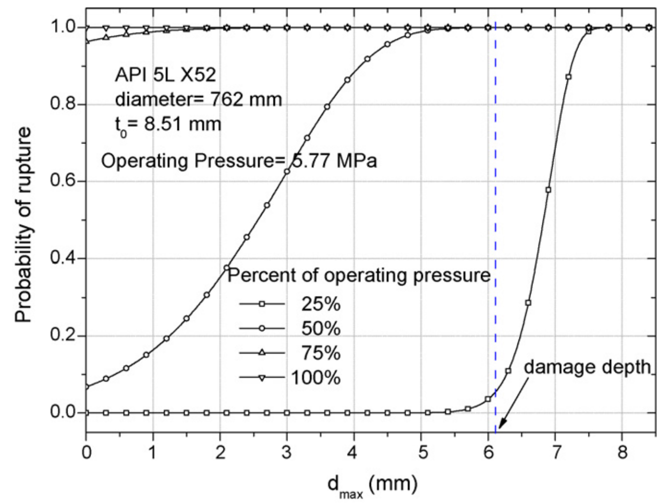


**Fig. 10.** Probability of rupture as a function of the depth of damage for different values of the operating pressure. The event corresponds to the National Transportation Safety Board report NTSB/PAR-03/01.

Mexico. The released gas ignited and burned for 55 min. Twelve persons who were camping under a concrete-decked steel bridge that supported the pipeline across the river were killed and their three vehicles destroyed. Two nearby steel suspension bridges for gas pipelines crossing the river were extensively damaged. According to El Paso Natural Gas Company, property and other damages or losses totaled $998,296. The National Transportation Safety Board determines that the probable cause of the August 19, 2000, natural gas pipeline rupture and subsequent fire near Carlsbad, New Mexico, was a significant reduction in pipe wall thickness due to severe internal corrosion. Following the mentioned report, we considered the following parameters: diameter = 762 mm, wall thickness = 8.51 mm, operating pressure = 5.77 MPa, loss wall thickness = 72% of wall thickness, length of damage = 6527.8 mm and grade = API 5L X52. Standard duct analysis indicated the values $p_{Plain} = 12.20$ MPa, and $g_d^{min} = 0.0$, $\nu_0 = 0.473$. The latter value indicates that the duct is operated at about 47% of its limiting resistance. Fig. 9 shows the rupture probability as a function of the corrosion damage depth for axial lengths corresponding to 25, 50, 75 and 100% of the nominal diameter. According to the publicly available report, it is known that the damage length is equal to 6527 mm, corresponding to 8.5 times the nominal duct diameter. In this way, the damage length can be considered as infinitely larger than the duct diameter. As shown in Fig. 9, the probability of failure for this event is equal to 1.0. Interestingly, the rupture failure could be occurred even for damage lengths of the order of 50% of the reported one. Our results suggest that, to reduce the risk of failure, the duct should be subjected to major maintenance several months before the rupture occurred; namely, when the length of damage was about 3000 mm. As an additional test, it was considered that the length of damage was of the order of the duct diameter. Fig. 10 shows the probability of failure as a function of the damage depth for different values of the operation pressure. It should be noted that the operation pressure was 5.77 MPa, corresponding to a pumping point. It can be observed that the pressure at which the duct failed was smaller than the operation pressure. This indicates that further variables (e.g., pump damage) might have a detrimental effect in the operation of the natural gas transportation system.

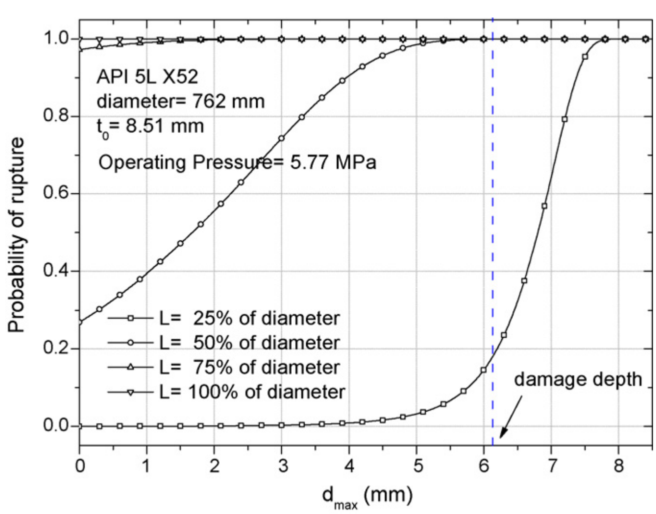


**Fig. 9.** Probability of rupture as a function of the depth of damage for different values of the length of damage. The event corresponds to the National Transportation Safety Board report NTSB/PAR-03/01.

Finally, as it stands, the modeling framework described in this work can be used for monitoring the risk of failure in pipelines. Several studies have shown that a systematic evaluation of pipelines in the oil industry can lead to a significant reduction of economical and environmental impacts [2,3,24]. On the other hand, it has been shown that failure events are not independent at all, but show some temporal correlations [25], indicating that once a pipeline is failing, the probability of further failures can be increasing. The application of the model for inspection data requires only few parameters of the geometry of the damaged pipe, which can be used to take decision on the extent of the maintenance policy for reducing potential catastrophic events with severe leakage of hazardous material, such as gas, gasoline, diesel and crude oil. To this end, the design of non-invasive methods for prompt detection of corroded pipelines, like the use of torsional guided lines [26], becomes of prime importance for an effective application of prediction failure methods as the one presented in this work.

## 5. Conclusions

This work proposed a hybrid framework, both deterministic and probabilistic, to identify the type of failure in damaged pipelines that transport hazardous material. The aim of the modeling approach was to design a reliable and simple procedure to estimate whether a pipeline failure can be of leakage or rupture type according to the pipe dimensions and the extent of the damaged surface on the duct. Experimental tests reported in the literature were used to calibrate the model and further experimental tests were used to evaluate the prediction capabilities. As an improvement with respect to the traditional deterministic Shannon's approach based on stress balance with effectiveness of the order of 60%, the present modeling procedure increased the prediction effectiveness to about 93%. Hence, the model proposed model approach can be used in practice for design, inspection, maintenance and substitution policies oriented to reduce the occurrence of events with catastrophic social, environmental and economical effects.

*List of symbols*

| | |
|---|---|
| $A$ | area of damaged surface in the axial direction |
| $A_0$ | area of the pipe wall |
| $d_{max}$ | maximum damage depth |
| $f'(\cdot)$ | posteriori probability distribution (Eq. (10)) |
| $g_d(\cdot)$ | correction function (Eq. (4)) |
| $l_0$ | damage axial length |
| $M$ | Folias factor |
| $P_L$ | probability that a pipe has a leak failure |
| $P_R$ | probability that a pipe has a rupture failure |
| $p_{Plain}$ | nominal (i.e., without corrosion effects) resistant pressure |
| $p_{LongGroove}$ | resistant pressure for an infinite longitudinal groove of a given depth |
| $p_R$ | rupture pressure |
| $r_0$ | interior pipe radius |
| $t_0$ | original (*i.e.*, without damage) wall thickness |
| $t_{ER}$ | equivalent wall thickness (Eq. (3)) |

*Greek*

| | |
|---|---|
| $\beta$ | random parameter in Eq. (7) |
| $\zeta$ | damage factor |
| $\xi_R$ | random variable with unit mean |
| $\sigma_\theta$ | hoop stress |
| $\sigma_Y$ | yield stress |

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