# RISK ANALYSIS TECHNIQUES OF OIL AND GAS PIPELINE

## TÉCNICAS DE ANÁLISIS DE RIESGO DE OLEODUCTOS Y GASODUCTOS

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## ABSTRACT

The safety of pipelines that transport energy has become an important and controversial issue with the general public. The main hazard for safe transportation of substances is a pipeline failure taken as a loss of its tightness and release of the transported medium to the environment. To perform reliability analysis and estimation of accident risk level, Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) are two graphical techniques used to perform a risk analysis, where FTA represents causes and their probabilities of failures, and ETA represents consequences of a failure event. Failure of oil transmission pipelines was analyzed by fault tree analysis in this project, and the probability of internal corrosion, one of the root causes, has been evaluated by applying the physical reliability model. According to failure modes of pipeline, leakage and rupture, a fault tree of the pipeline was constructed. Minimal cut sets of the fault tree have been shown, and the failure probability of a top event and the important analyses of basic events were evaluated by quantitative analysis. In conventional fault tree analysis, probabilities of the basic events were treated as precise values. At last, the probability of different accident scenarios that may result from failed oil pipeline due to pipe rupture has been estimated.

**Keywords**: Reliability analysis; Risk analysis; Fault tree; Event tree; Physical reliability model; Corrosion; Oil pipeline rupture.

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## RESUMEN

La seguridad de las tuberías que transportan energía se ha convertido en un tema importante y controvertido para el público en general. El principal peligro para el transporte seguro de sustancias es el fallo de una tubería entendida como pérdida de estanqueidad y liberación del medio transportado al medio ambiente. Para realizar el análisis de confiabilidad y la estimación del nivel de riesgo de accidentes, el Análisis de árbol de fallas (FTA) y el Análisis de árbol de eventos (ETA) son dos técnicas gráficas que se utilizan para realizar un análisis de riesgo, donde FTA representa las causas y sus probabilidades de fallas, y ETA representa las consecuencias de un evento de falla. La falla de los oleoductos de transmisión se analizó mediante un análisis de árbol de fallas en este proyecto, y la probabilidad de corrosión interna, una de las causas principales, se evaluó mediante la aplicación del modelo de confiabilidad física. De acuerdo a los modos de falla de la tubería, fuga y ruptura, se construyó un árbol de fallas de la tubería. Se han mostrado conjuntos de cortes mínimos del árbol de fallas, y la probabilidad de falla de un evento principal y los análisis importantes de eventos básicos se evaluaron mediante análisis cuantitativo. En el análisis de árbol de fallas convencional, las probabilidades de los eventos básicos se trataron como valores precisos. Por último, se ha estimado la probabilidad de los diferentes escenarios de accidentes que pueden resultar de la falla del oleoducto debido a la ruptura de la tubería.

**Palabras clave:** Análisis de confiabilidad; Análisis de riesgo; árbol de fallas; árbol de eventos; Modelo de confiabilidad física; Corrosión; Rotura de oleoducto.

## INTRODUCTION

Oil and Gas are the major sources of fuel around the world. Using pipelines is the main way transporting of oil and gas, and pipelines play a critical role in the petroleum industry providing safe, reliable and economical transportation. As the need for more energy increases and population growth continues to get further away from supply centers, pipelines are needed to continue to bring energy to us. Only in Canada, the length of pipelines is approximately 100,000 km.

Although transport using pipelines is considered one of the safest methods of long-term transport, available databases of accidents reveal that the risk associated with pipeline operation is often on the same level as that of stationary refinery installation. Pipelines are mainly installed underground, and the main causes affecting their performance and safety are corrosion, interference from the third party (human error) and natural hazards. Previous works show that most pipelines fail in a mode of leakage, puncture, or rupture. Because of the combustible, explosive and diffusible characteristics of oil and gas, failure of pipelines has severe consequences such as human fatality, environmental pollution and economic loss.

On December 11, 2012, a buried 20-inch-diameter interstate natural gas transmission pipeline, ruptured in a sparsely populated area. The escaping high-pressure natural gas ignited immediately. Three houses were destroyed by the fire, and several other houses were damaged. There were no fatalities or serious injuries. About 76 million standard cubic feet of natural gas were released and burned. Columbia Gas Transmission Corporation reported the cost of pipeline repair was $2.9 million, the cost of system upgrades to accommodate in-line inspection was $5.5 million, and the cost of gas loss was $285,000. It has been discussed that the probable cause of the pipeline rupture was (1) external corrosion of the pipe wall due to deteriorated coating and ineffective cathode protection and (2) the failure to detect the corrosion because the pipeline was not inspected or tested after 1988.

On September 9, 2010, a 30-inch-diameter segment of an intrastate natural gas transmission pipeline known as Line 132, owned and operated by the Pacific Gas and Electric Company, ruptured in a residential area in San Bruno, California. The rupture produced a crater about 72 feet long by 26 feet wide. The company estimated that 47.6 million standard cubic feet of natural gas were released. The released natural gas ignited, resulting in a fire that destroyed 38 homes and damaged 70. Eight people were killed, many were injured, and many more were evacuated from the area. The National Transportation Safety Board determines that the probable cause of the accident was the company's (1) inadequate quality assurance and quality control in 1956 during its Line 132 relocation project, which allowed the installation of a substandard and poorly welded pipe section with a visible seam weld flaw that, over time grew to a critical size, causing the pipeline to rupture during a pressure increase stemming from poorly planned electrical work at the Milpitas Terminal; and (2) inadequate pipeline integrity management program, which failed to detect and repair or remove the defective pipe section.

To perform reliability analysis and estimation of accident risk level, three methods; quantitative, semi-quantitative and qualitative, can be used. Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) are two graphical techniques used to perform a risk analysis, where FTA represents causes and their probabilities of failures, and ETA represents consequences of a failure event. In this study, we apply probabilistic risk analysis techniques such as FTA and ETA to investigate the root causes of oil pipeline ruptures and potential consequences. The required probabilities are either taken from the available literature or calculated using physical reliability models.

## LITERATURE REVIEW

Han and Weng (2010) have proposed a method that is composed of the probability assessment of accidents, the analysis of consequences and the evaluation of risk. The consequences analyzed include those of the outside and inside gas pipelines. The analysis of consequences of the outside pipelines focuses on the individual risk and societal risk caused by different accidents, while those of the inside pipelines are concerned about the risk of the economic loss because of the pressure re-distribution. The risk of a sample urban gas pipeline network is analyzed to demonstrate the presented method. They have concluded that the results show that the presented integrated quantitative risk analysis method for the natural gas pipeline networks can be used in practical applications.

Failure of oil and gas transmission pipelines was analyzed by fault tree analysis by Yuhua and Dotoa (2004) According to failure modes of pipeline leakage and rupture, a fault tree of the pipeline was constructed. Fifty-five minimal cut sets of the fault tree had been achieved by qualitative analysis, while the failure probability of a top event and the important analyses of basic events were evaluated by quantitative analysis. In conventional fault tree analysis, probabilities of the basic events were treated as precise values, which could not reflect the real situation of the system because of ambiguity and imprecision of some basic events. In order to overcome this disadvantage, a new method was proposed that combined expert elicitation with fuzzy set theories to evaluate the probability of the events. The method given in this article is effective FTA is an effective way to assess the safety and reliability of the complex systems, in which fuzzy is an objective issue. A way to handle the fuzzy problems in the FTA had been provided in this paper by combing expert elicitation with fuzzy set theory. In expert elicitation, due to different experiences and knowledge about the pipeline of the experts, a weighting factor was introduced. The triangular fuzzy number was used to represent a fuzzy characteristic of failure probabilities of the basic events and important analyses of the basic events indicate that quality of manufacturing pipe, quality of welding, and installation of pipeline and percentage of inclusion play important roles in affecting failure of the pipeline and pipeline material, mechanical damage also affect the pipeline to a large extent. They included that the method given in this paper decreases error in conventional fault tree analysis, which treats the failure rate of all basic events as exact values treating fuzzy events of FTA.

In Anjoman Shahriar et al. (2011)'s paper, in order to deal with the vagueness of the data, fuzzy logic is employed to derive fuzzy probabilities (likelihood) of basic events in the fault tree and to estimate fuzzy probabilities (likelihood) of output event consequences. The study also explores how interdependencies among various factors might influence analysis results and introduces fuzzy utility value (FUV) to perform a risk assessment for natural gas pipelines using triple bottom line (TBL) sustainability criteria, namely, social, environmental and economic consequences. The study aims to help owners of transmission and distribution pipeline companies in risk management and decision-making to consider multi-dimensional consequences that may arise from pipeline failures. The research results can help professionals to decide whether and where to take preventive or corrective actions and help informed decision-making in the risk management process.

Dziubinski et al. (2005) presented a methodology of risk assessment for hazards associated with transportation of dangerous substances in long pipelines. The proposed methodology comprises a sequence of analyses and calculations used to determine basic reasons of pipeline failures and their probable consequences, taking individual and societal risk into account. A specific feature of this methodology is a combination of qualitative (historical data analysis, conformance test and scoring system of hazard assessment) and quantitative techniques of pipeline safety assessment. This enables a detailed analysis of risk associated with selected hazard sources by means of quantitative techniques. On the ground of the methodology typical problems that usually pose serious threat and constitute part of risk analysis for long fuel pipelines are also presented. The authors realise that the environmental hazard assessment for long pipelines requires individual approach in every case. This is determined mainly by a changing specificity of pipeline location. It refers particularly to the calculation of consequences of hazardous substance release for particular ecosystems (air, water, soil).

In A. Amirata et al. (2005)'s study, the residual stress distribution in large diameter pipes has been characterized experimentally in order to be coupled with the corrosion model. During the pipe lifetime, residual stress relaxation occurs due to the loss of pipe thickness as material layers are consumed by corrosion. The reliability-based assessment of residual stress effects is applied to underground pipelines under a roadway, with and without active corrosion. It has been found that the residual stress greatly increases the failure probability, especially in the early stage of the pipe lifetime. The main results of this study can be summarized as follows:

1. Up-rating pressure when neglecting residual stresses increases drastically the failure probability. Moreover, at high pressures, the failure probability is sensitive to the coefficient of variation of gas pressure. In this case, if the variance increases, the pressure should be decreased to maintain the safety level. However, for low-pressure levels, even with a large coefficient of variation, the failure probability is not significantly affected.
2. the most sensitive parameters are gas pressure, yield strength, internal radius, thickness and residual stress. Among these variables, the most important for pipeline safety is gas pressure which increases largely with up-rating.
3. When pressure is increased, the sensitivities

to residual stress and internal diameter vary in opposite directions. For low-pressure, the residual stress sensitivity is much higher than for internal diameter. With pressure increase, a redistribution of both sensitivities is observed, and for very high pressures, both of them converge to a low influence (8.5% for the specific example in this paper).

4. As expected, the corrosion rate produces a large increase in failure probability, especially in the early stage of the pipe lifetime. The effect of residual stress relaxation increases the safety margin of the pipeline, which tends to balance the strength losses. In this sense, the residual stress can be seen as a reserve of strength to be released with time.
5. The failure probability becomes less sensitive when residual stresses are considered. In fact, neglecting the residual stresses puts all the reliability weight on the other variables (especially pressure), which makes the probability evaluation more sensitive. That means, the consideration of residual stresses implies a better redistribution of the reliability importance factors, leading to a less sensitive failure probability.
6. For high corrosion rates, the influence of residual stresses with time exposure is lost in less than 20 years. In fact, the residual stress is relaxed because of thickness loss due to corrosion attacks. However, for low corrosion rates, the importance of residual stresses still remains significant during the whole lifetime.

## PROBABILISTIC RISK ANALYSIS TECHNIQUES

### Fault Tree

Fault Tree is a deductive, structured methodology to determine the potential causes of an undesired event, referred to as the top event. The top event usually represents a major accident causing safety hazards or economic loss. While the top event is placed at the top of the tree, the tree is constructed downwards, dissecting the system for further detail until the primary event leading to the top event is known. Primary events are considered binary (with two states) and statistically independent In an FT, the relationships between events are represented by means of gates, of which AND-gates and OR gates are the most widely used.

Once completed, the FT can be analyzed both qualitatively and quantitatively. In the qualitative evaluation, using Boolean algebra, an expression is derived for the top event in terms of combinations of primary events. In the quantitative part, the probability of the top event is expressed in terms of the occurrence probability of the primary events or in terms of the minimal cut-sets. Small FTs can be evaluated manually; however, large and complex FTs require the aid of computerized methods for evaluation. Methods for FT analysis include the analytical method, Monte Carlo simulation, and binary decision diagram. Due to limitations in using the Monte Carlo simulation, an analytical approach (e.g., minimal cut-sets determination) is more frequently used for the evaluation of an FT. To reduce the margin of error due to inaccuracy and incompleteness of the data of the primary events, some authors have recently used fuzzy set theory and evidence theory in FT analysis.

### Gates and Boolean algebra

Fault trees are built using gates and events. The two most commonly used gates in a fault tree are the AND and OR gates. As an example, consider two events comprising a top event (or a system). If the occurrence of either event causes the top event to occur, then these events are connected using an OR gate. As a result, the probability of the top event would be equal to the union of the events' probabilities. On the other hand, if both events need to occur to cause the top event to occur, they are connected by an AND gate. Accordingly, the probability of the top event would be equal to the intersection of the events' probabilities. As a visualization example, Figure 1 shows the two typical AND (left) and OR (right) gates and their corresponding Boolean algebra.

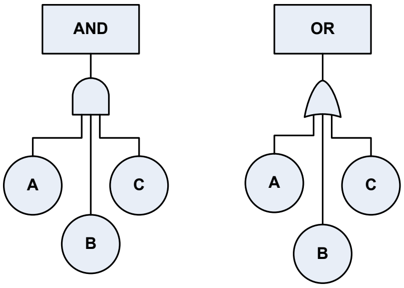

Figure 1. AND gate (left) and OR gate (right) in fault trees

Since conventional fault trees are unable to consider conditional dependencies, the events in such fault trees are presumably considered independent. As a result, the corresponding Boolean algebra for AND gate and OR gate will be:

$$P(AND) = P(A \cap B \cap C) = P(A)P(B)P(C) \quad (1)$$

$$P(OR) = P(A \cup B \cup C) = 1 - (1 - P(A))(1 - P(B))(1 - P(C)) \quad (2)$$

It is worth noting that in the case of having more than three events, the respective relationship for an OR gate could be written as:

$$P(A_1 \cup A_2 \cup \ldots \cup A_n) = 1 - \prod_{i=1}^{n}(1 - P(A_i)) \quad (3)$$

It should be noted that conventional fault trees usually underestimate or overestimate the probability of top events due to their inability in considering conditional dependencies. For example consider the fault tree in Figure 2, in which the intermediate events X1 and X2 share the root event A. A is usually considered a common-cause failure.

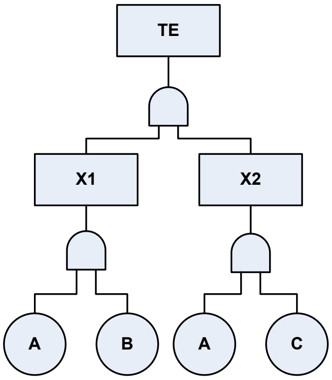

Figure 2. A fault tree with common-cause failure A. According to the logical relationship embedded in AND gate, the probabilities of X1 and X2 will be

$$P(X1) = P(A)P(B) \quad (4)$$

and

$$P(X2) = P(A)P(C) \quad (5)$$

Consequently, assuming that X1 and X2 are independent (which is the common assumption in the fault tree) the probability of TE (Top Event) will be calculated as:

$$P(TE) = P(X1 \cap X2) = P(X1)P(X2) = P(A)^2P(B)P(C) \quad (6)$$

However, as we know, X1 and X2 are not independent since they share the common cause A. As a result:

$$P(TE) = P(X1 \cap X2) = P(X1)P(X2|X1) = P(A)P(B)P(C) \quad (7)$$

Comparing the probabilities of the top event given by Equations (6) and (7), it can be seen that the fault tree in Figure 2 underestimates the top event by a factor of P(A). Similarly, if X1 and X2 were connected to TE by means of an OR gate, the respective probability would be overestimated instead. Although such limitations of conventional fault trees can be relaxed by relying on state-dependent methods such as Markov chains and Bayesian networks.

## Event Tree

Event tree analysis (ETA) is an analysis technique for identifying and evaluating the sequence of events in a potential accident scenario following the occurrence of an initiating event. ETA utilizes a visual logic tree structure known as an event tree (ET). The objective of ETA is to determine whether the initiating event will develop into a serious mishap or if the event is sufficiently controlled by the safety systems and procedures implemented in the system design. An ETA can result in many different possible outcomes from a single initiating event, and it provides the capability to obtain a probability for each outcome.

ETA is a binary form of a decision tree for evaluating the various multiple decision paths in a given problem. ETA appears to have been developed during the WASH-1400 nuclear power plant safety study (Circa, 1974). The WASH-1400 team realized that a nuclear power plant probabilistic risk analysis could be achieved by FTA; however, the resulting fault trees would be very large and cumbersome, and they, therefore, established ETA to condense the analysis into a more manageable picture, while still utilizing FTA.

ETA has been successfully applied to a wide range of systems, such as nuclear power plants, spacecraft, and chemical plants. Considering an undesired event as the initiating event (IE) of an event tree, there will be two branches at every top event (TE) or safety measure. These branches usually represent the failure/function or present/absence of safety measures or occurrence/non-occurrence of a sequence of events. Figure 3 illustrates a typical ET with one IE and two TEs. As a result, four outcomes or consequences could have been envisaged, C1, C2, C3, and C4.

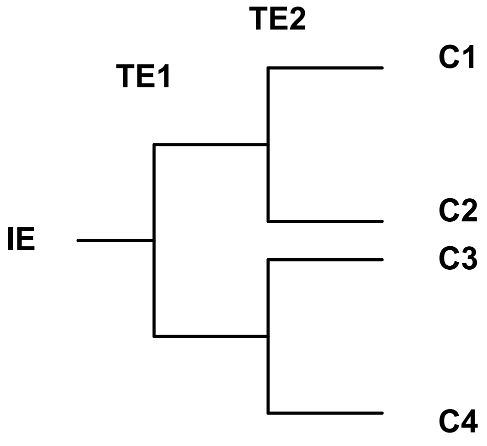

Figure 3. A typical event tree.

Having the required probabilities, the probabilities of consequences can readily be calculated. For example, the probabilities of C1-C4 in Figure 3 can be calculated as:

$$P(C1) = P(IE).(1 - P(TE1)).(1 - P(TE2)) \tag{8}$$

$$P(C2) = P(IE).(1 - P(TE1)).P(TE2) \tag{9}$$

$$P(C3) = P(IE).P(TE1).(1 - P(TE2)) \tag{10}$$

$$P(C1) = P(IE).P(TE1).P(TE2) \tag{11}$$

In an ET usually the last consequence (e.g., C4 in Figure 3) has the lowest probability and the highest severity.

## Physical Reliability Models

Physical reliability models aim to explain the reliability (or failure) of a component as a multivariate function of operational physical parameters. Physical models, particularly structural models, mechanical models, and physics-of-failure models have long been recognized in reliability and maintainability analysis in civil and mechanical engineering. The design of machines and structures is one of the oldest applications of engineering sciences. Unique engineering systems such as the long span bridges were designed and constructed during the last toe centuries demonstrating not only a high level of engineering decision but also a high accuracy of structural analysis. This accuracy was provided by successful development of elasticity theory, structural mechanics, and other branches of applied mechanics.

There are several methods in physical reliability models such as covariate models, static models, and dynamic models. Static models, against covariate and dynamic models, do not consider time as an influential parameter and only count on the component's strength and stresses. Similar to covariates, stresses are often considered as physical or chemical parameters affecting a component's operation. Strength is defined as the highest amount of stress that a component can bear. According to the definitions of stress and strength, a failure occurs when the stress on the component exceeds its strength (Ebeling, 1997). Both stress and strength can be constant or considered as random variables having respective probability distribution functions. For example, the failure probability of component Q having a random strength Y~f_Y (y), and being under a random stress X~f_X (x), would be:

$$Probability\ of\ failure = \Pr(Y \le X) = \int_0^{\infty} \int_0^{X} f_Y(y)dy\, f_X(x)dx \quad (12)$$

## METHODOLOGY

### Fault tree development

According to the available accident reports and previous work, two main failure modes were identified for oil and gas pipelines: puncture and rupture. Considering the rupture as the more hazardous failure mode due to the possibility of larger oil and gas leakages, the main contributing root causes were identified and logically connected to each other by means of a fault tree as shown in Figure 4.

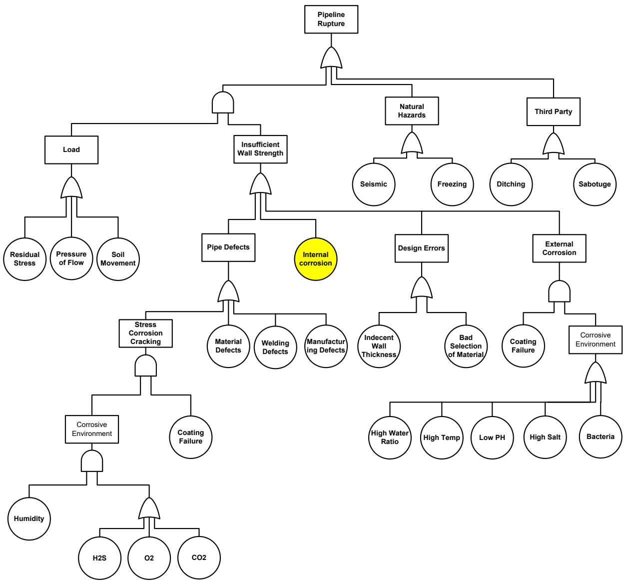

Figure 4. Developed fault tree for oil pipeline rupture

Considering the "pipeline rupture" as the top event, the main contributing factors were loads along with insufficient wall strength, natural hazards such as seismic and freezing which are predominant according to the operational and environmental conditions of Canada, and third party intervention. The foregoing contributing factors were further decomposed to lower level intermediate events and root causes. However, it should be noted that some factors such as sabotage and seismic were not further decomposed to their root causes since their probabilities could have been elicited from the literature. The corresponding probabilities of the root causes of the fault tree in Figure 4 have been tabulated in Table 1. Performing the fault tree analysis and considering conditional independencies, the probability of the top event, i.e., pipeline rupture, is calculated as 1.98 E-01. Assuming that the only failure mode of the pipeline would be the rupture, the reliability of the oil pipeline would be equal to $1 - 1.98E - 02 = 0.9802$.

Table 1. Probabilities of root causes in the fault tree of Figure 4.

| Root Events | Probability |
|---|---|
| Residual Stress | 5.62E-06 |
| Soil Movement | 5.65E-02 |
| Pressure of Fluid | 5.16E-06 |
| Material Defects | 9.44E-01 |
| Manufacturing Defects | 1.35E-01 |
| Welding Defects | 1.08E-01 |
| Indecent Wall thickness | 1.54E-02 |
| **Internal corrosion** | **3.00E-05** |
| Bad selection of Material | 7.84E-02 |
| Failure of Coating | 2.09E-08 |
| Sabotage | 4.36E-02 |
| Freezing | 2.10E-02 |
| Ditching | 7.21E-02 |
| Seismic | 2.39E-02 |
| High Temperature | 1.38E-09 |
| High Water Ratio | 5.75E-09 |
| High Salt | 2.91E-09 |
| Low PH | 2.99E-09 |
| Bacteria | 2.53E-09 |
| Humidity | 1.99E-05 |
| CO2 | 2.22E-06 |
| H2S | 1.41E-05 |
| O2 | 3.52E-06 |

Considering the fault tree of Figure 4 two points are worth noting. First, since the conventional fault trees such as the one depicted in Figure 4 cannot consider dependencies, the probability of the top event could be either underestimated or overestimated, depending on the type of logical gates. For example, the root cause of "coating failure" is common to both intermediate events "External corrosion" and "Stress corrosion cracking". Since these two intermediate events are finally connected to the higher level intermediate event "Insufficient wall strength" via an OR gate, it is expected that the probability of "Insufficient wall strength" has been overestimated, which in turn leads to an overestimation of the top event probability. Such a limitation can be relaxed by substituting state-dependent techniques able to consider dependencies, such as the Bayesian network (Khakzad et al., 2011, 2013).

Second, in Table 1, the probabilities of all the root causes have been adopted from the literature except "Internal corrosion", the probability of which has been calculated using static physical reliability models in order to demonstrate the potential application of such methods in probabilistic risk and reliability analysis. In the next section, we illustrate how physical reliability models can be used for this purpose.

## Application of physical reliability models

To calculate the probability of internal corrosion in Figure 4 (it has been shaded for the sake of better visual identification), we apply the concept of static physical reliability models based on a comparison between the strength of the component of interest (pipeline in this work) and the stress the component is subjected to. For this purpose, it is assumed that from an internal corrosion point of view the pipeline wall's initial thickness can be considered as the strength, denoted by t_0, while the reduction in the wall thickness can be considered as the stress, represented by t_c. It is also assumed that the pipeline failure (rupture) takes place when the corrosion-induced thickness reduction is greater than or equal to %20 of the initial thickness. In other words:

$$\Pr(\mathit{internal\ corrosion}) = \Pr(t_0 - t_c \le 0.8\, t_0) = \Pr(0.2t_0 - t_c \le 0) \quad (13)$$

In previous works, $t_0$ has been considered as a normal random variable having a mean value between 1.05 and 1.95 cm and a variance equal to 0.1 cm. Thus, in the present study we adopt the following normal distribution for $t_0$:

$$t_0 \sim \mathit{Normal}\ (1.95, 0.1) \quad (14)$$

Further, a power law has been considered for the reduction in the wall thickness as:

$$t_c = kT^n \quad (15)$$

where T is time (year); k is a normal random variable $k \sim \mathit{Normal}\ (0.066, 0.037)$ and $n = 0.837$. If the failure probability for one year is to be calculated, i.e., T = 1, $t_c$ will also have a normal distribution equal to that of k:

$$t_c \sim \mathit{Normal}\ (0.066, 0.037) \quad (16)$$

As we know, summation or deduction of two or more normally distributed random variables results in a normal random variable. For example, if $X{\sim}N(\mu_x, \sigma_x)$ and $Y{\sim}N(\mu_y, \sigma_y)$ and $W = X \pm Y$, then $W{\sim}N(\mu_x \pm \mu_y, \sqrt[2]{\sigma_x^2 + \sigma_y^2})$.

Further, $aX{\sim}N(a\,\mu_x, \sqrt{a}\,\sigma_x)$ where a is a constant.

Thus, if $W = 0.2t_0 - t_c$, then $W{\sim}N(\mu_w = 0.2 \times 1.95 - 0.066,\ \sigma_w = \sqrt{0.2 \times 0.1^2 + 0.037^2})$, and $W{\sim}N(0.324, 0.058)$ (17)

As a result, the probability of failure can be re-written as:

$$\Pr(0.2t_0 - t_c \le 0) = \Pr(W \le 0) = \Pr\left(\frac{W-\mu_w}{\sigma_w} \le \frac{0-0.324}{0.058}\right) = \Pr(Z \le -5.59) = \phi(-5.59) = 0.00003 \quad (18)$$

This probability has been highlighted in bold in Table 1.

### Application of event tree

As previously mentioned, the event tree has extensively been applied in risk and reliability analysis to explore the consequences of an accident or an undesired event (Khakzad et al., 2014a, b). In the present work, we applied an event tree to foresee the potential consequences resulting from an oil pipeline rupture.

Taking the “pipeline rupture” as the event tree initiating event, a number of outcomes can be envisaged based on the operation/failure or presence/absence of a set of safety measures (or event tree top events). For example, having a rupture, the volume of released oil depends on the size of the rupture. In other words, the question that could be asked is: is the size of the rupture small or large? when we reach this top event, the upper branch represents a small-size rupture while the lower branch stands for a large-size rupture.

Further, depending on the presence or absence of a trench along the pipeline, the extent (area) of the released oil can be controlled. Thus, in the case of leakage or pool fire, the extent of the accident would be limited to the lateral diameter of the trench, significantly mitigating the adverse effects in terms of polluted area or extent of a potential pool fire. Reaching this top event, the upper branch refers to the present while the lower branch denotes the absence of such safety measures.

Finally, depending upon whether an ignition source is met or not, a pool fire can take place or an oil pool can form. In the former case, the fire engulfment and heat radiation would be the most important hazards threatening the pipeline itself and nearby facilities, environment (forest, farm, etc.), and humans (if the pipeline rupture occurs within residential areas), whereas in the latter case the most significant threat would be environmental pollution in the form of soil pollution, underground water aquifers, and surface waters (if rupture takes place near-surface waters such as rivers and seas). The upper branch represents the absence of an ignition source while the lower branch addresses the presence of such a hazard. Taking into account the initiating event and above-mentioned top events, possible outcomes would be in the form of small, medium, and large oil puddles (pools) or small, medium, and large pool fires. The probabilities of the top events along with the consequences have been listed in Table 2. As can be seen, the most probable consequence would be a medium pool (9.7 E -02) while the list probable consequence would be a large pool fire (1.9 E -05).

Table 2. Probabilities of the top events and consequences of the event tree.

| Top Events and Consequences | Probability |
|---|---|
| Size of Rupture (Small) | 9.90E-01 |
| Size of Rupture (Large) | 1.00E-02 |
| Trench (Yes) | 5.00E-01 |
| Trench (No) | 5.00E-01 |
| Ignition (Yes) | 2.00E-02 |
| Ignition (No) | 9.80E-01 |
| Small pool | 9.60E-02 |
| Medium pool | 9.70E-02 |
| Large pool | 9.70E-04 |
| Small pool fire | 1.90E-03 |
| Medium pool fire | 1.90E-03 |
| Large pool fire | 1.90E-05 |

## CONCLUSIONS

Reliability analysis is an effective tool to assess the risk and reliability of systems used in industry. Fault tree and event tree are two widely-used and practical tools in reliability analysis providing the probable causes of a failure and its relative consequences with their probability. Although the formalism of the fault tree approach does not allow for the incorporation of dependencies and conditional probabilities, it is still the most popular technique in preliminary risk and reliability studies due to its transparent and easyto-understand structure. Compared to the fault tree, the event tree is better able to incorporate conditional dependencies. However, being devoted to binary top events (i.e., having only two branches for each top event) has limited its application in consequence analysis of ternary top events and multi-state systems.

In this study, we took advantage of conventional yet popular fault tree and event tree analysis to reliability analysis and risk assessment of an oil pipeline subjected to rupture failure mode. To this end, through an exhaustive review of available accident reports and previous works, the most important root causes of the rupture were identified and illustrated in the form of a fault tree. Using the Boolean algebra and logical relationships embedded in the fault tree approach and taking into account the root-cause probabilities elicited from the literature, the probability of oil pipeline rupture was calculated. We also demonstrated when the required probabilities could not be found in the literature, other reliability techniques such as physical reliability models can be considered for such purpose. To this end, we applied a static physical reliability model to calculate the probability of internal corrosion based on a comparison between the strength (pipeline wall thickness) and stress (corrosion-induced thickness reduction). This study proved that physical reliability models can effectively be applied in the reliability analysis of components experiencing wear-out failure modes such as corrosion. In this research, we also found that the main causes of pipeline rupture are design factors and material defects, in addition to the corrosion which plays an important role in time-dependent (wear-out) pipeline rupture. Having the probability of puncture and assuming that the puncture is the sole failure mode of oil pipelines, the reliability of the pipeline can be readily calculated as the unity minus the probability of puncture.

We also took another step further by performing a risk analysis study in which the potential consequences of the pipeline rupture were sought using an event tree approach. It was found that among the possible consequences the medium size pool has the highest while the large size pool fire has the lowest probability.

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