Reliability of a Polethylene Pipe on the Basis of the PENT Model

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Abstract

Today it is recognized that SCG is the most expected origin of failure in transport systems using HDPE pipes. According to the PPI, the PENT (Pennsylvania Notch Test - ASTM D 1473) is a laboratory test performed to measure the slow crack propagation resistance SCG. In the present study, a probabilistic approach based on the PENT test is adopted to study the reliability of a polyethylene pipe. The estimated lifetime is calculated on a reliability-model. Several parameters are used to establish parametric analysis such as crack length, pressure and service temperature. The aim is mainly to use probabilistic tools to estimate the HDPE pipe lifespan reliably i.e. operating safely service. β the reliability index is calculated based on the crack size. PENT test was considered, the values obtained from β are limited (the majority not accepted) according to the length of the crack. We note that for values of 100 µm <a <400 µm, the reliability index is very small which takes us away from the β value close to 3.7272 recommended by manufacturers.

Keywords
Pipe, Crack, PENT model, PHIMECA, Reliability index.

1. Introduction

High Density Polyethylene (HDPE) is a thermoplastic material commonly used for pipe structures. There are two modes of failure of a pipeline system: (i) Rapid Crack Propagation (RCP) that could affect a significant length of the pipeline, and (ii) Fragile system failure due to slow crack growth (SCG) initiated following a pre-existing defect in the pipe causing the local fragile fracture (Nezbedova et al. 2009). These two modes of rupture depend on the age of the structure, the service environment and the operating conditions. In pressurized plastic pipe applications, a majority of fractures are attributed to slow crack growth (SCG). It is a brittle fracture that is characterized by stable growth with few macroscopic plastic deformations (Rajendra et al. 2002). Understanding the mechanism allows making predictions and tests simulating the phenomenon. In fact, the SCG has resulted in standards for plastic tubes. The highest practical problems close to the usage of HDPE pipe counting early failure owed to SCG were recognized as illustrated: (i) Consequence of high temperature, (ii) Consequence of appropriate defect size (not more than 10% of wall width), (iii) a margin of security against risks in analytical models design (safety factor) (Krishnaswamy et al. 2012).

In service, the life generally required in water distribution networks and natural gas covers a period up to 50 years. It is clear that pressure pipe applications require polymers with a very long life. Only, the problem lies in the development of adequate tests that are able to simulate the mechanism taking place and estimate the lifetime in a relatively short time (Chudnovsky et al. 2012, Pi et al. 2018). Crack initiation (CI) and slow crack growth

(SCG) represent the most desirable failure or failure approaches in long-term applications of thermoplastic pipes under pressure. Increasing demand for new accelerated (short-term) characterization methods to describe crack initiation resistance and SCG for realistic lifetime prediction (long-term). Various static laboratory tests such as the Notched Pipe Test (NPT, ISO 13479), the Pennsylvania Notch Test (PENT, ISO 16241, ASTM F1473) or the Full Notch Creep Test (FNCT, ISO 16770) have been developed. Cyclic fatigue accelerated tests "fatigue" were performed and in particular with samples in the form of cracked round bars (CRB). These laboratory tests have shown a great potential for a rapid classification of the different qualities of PE tubes, even in applications at temperatures close to 23 ° C and without any additional constraints such as the existence of an aggressive environment (A. Frank, 2010, Frank et al. 2019). In all models and tests, high temperature is chosen as an hastening cause in short-term experiments based on the time-temperature superimposition standard (TTSP) in the long-term forecast. The simulations now existing for predicting the service life of PE pipes can be divided into three groups: (1) RPM: Rate Process Method, (2) Bi-Directional Shift Approach, and (3) fracture mechanics methods. In the latter category, there are several approaches: "The PENT-Correlation Service Life" and "Integration of Time to Initiation and Growth Flaw to Failure" (R. Visser, 2009). Table 1 summarizes some of the models considered for the evaluation of service life. Generally, there is not a great covenant among models and sometimes the calculation of specific parameters is not obvious.

Table 1. Available mathematical models for plastic pipe lifetime estimation (L. Alimi, K. Chaoui, 2018).

Case	Method	Abrev.	Equation	Comments
1	Rate Process Method	RPM	$\log t_f = A + \frac{B}{T} + \frac{C \log \sigma}{T}$	At least 2 burst tests (with ≠T°) ISO 9080
2	Popelar Shift Method	PSM	$a_T = Exp\left[-0.109 \cdot (T - T_R)\right]$ $b_T = Exp\left[0.0116 \cdot (T - T_R)\right]$	Important effect of temperature
3	Fracture Toughness	KIC, LIMIT	$\frac{da}{dt} = AK_I{}^m$	Difficulty: "a" and "K" measurements
4	Pennsylvania Edge-Notch Test	PENT	$t_f = t_{PENT} \cdot \left[\frac{0.468}{K}\right]^n . Exp\left[\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{353}\right)\right]$	Difficulty: initiation time ASTM F1473
5	Time to flaw initiation and growth to failure	CI + CP	$\ln\left(\frac{t_T}{t_{20}}\right) = \ln \frac{\left(\frac{da}{dt_{20}}\right)}{\left(\frac{da}{dt_T}\right)} = 12515\left(\frac{1}{T} - \frac{1}{293}\right)$	Difficulty: crack initiation definition (microscopy)
6	Slow Crack Propagation	SCG	$t_f = t_{tot} \approx t_{init} + \frac{2}{A \cdot (m-2) \cdot Y^m} \cdot a_{init}{}^{(2-m)/2} \cdot \sigma^{-m}$	Difficulty: "a" and "K" measurements

The probabilistic approach of structural reliability is essential. Risk is assessed as a probability rather than as a judgment (the design is acceptable or not, the operation can be continued or not). The calculation of this probability makes it possible to reduce the risk of failure through the organization of maintenance-inspection programs, to extend the operating life by optimizing their use (P. Chapouille, 2004, Alimi et al. 2017, Alimi et al. 2018).

Studying the behavior of buried pipes in the soil is a function of many parameters such as; the laying conditions, local geotechnical conditions, accidental overloads. All these mentioned parameters are indeed poorly controlled, and therefore are considered as random events. Different situations of the tube may be source of danger and generate, under certain conditions for accidents or breakdowns especially the structural defects present within the pipe. Service anomalies cause problems with network malfunction. It is from these different situations found during the work of a polyethylene pipe that a study of its rupture is carried out through a mechanic-reliability model as it is explained in the following section.

The reliability index of polyethylene pipes buried in the ground, and subjected to an internal pressure, is calculated without taking into account the variation of the temperature. Determining the weight or sensitivity of a variable can describe the impact of its evolution on the condition of the tube. The objective is to rank the most significant variables which are significant in the characterization of mechanical behavior and reliability engineer. At the border, the reliability index is 3.7272, corresponding to a P_f failure probability approaching 10^{-4} as shown in Table 2. The reliability index β varies from 0 to 7, any value less than 0 and greater than 7 is considered insignificant.

Table 2. Values probability failure P_f as a function of the reliability index β.

β	P_f
0.0	0.5000
0.5	0.30854
1.0	0.15866
1.5	0.06681
2.0	0.02275
2.5	0.00621
3.0	0.00135
3.5	$2.33\text{x}10^{-4}$
4.0	$3.17\text{x}10^{-5}$
4.5	$3.40\text{x}10^{-6}$
5.0	$2.87\text{x}10^{-7}$
6.0	$9.87\text{x}10^{-10}$
7.0	$1.28\text{x}10^{-12}$

Reliability index β is calculated using the PHIMECA Software based on a FORM / SORM approach. This index represents a measure of the margin with respect to the probability of failure (Table 2) (Fiabilité des structures des installations industrielles). In this paper the PENT model is adopted to assess the mechanical reliability of a polyethylene structure.

2. Mechanical model

The assessment of PENT life is based on a mathematical model that uses experimental results provided during a PENT test. According to the PPI, the PENT (Pennsylvania Notch Test - ASTM D 1473) is a laboratory test performed to measure the slow crack propagation resistance SCG. A sample is cut from a compression molded plate or directly extracted from the tube. It is precisely notched and then exposed to a constant tensile stress of 2.4 MPa (348 psi) at a temperature of 176 ° F (80 ° C) (Figure 1). The break time is recorded, and then a correlation between this time and the life of the pipe is established under the actual service conditions. The lifetime or break time is given by Equation 2 with properties already established (Dominguez et al. 2012, Nezbedova et al. 2009, ASTM F1473-07, 2007):

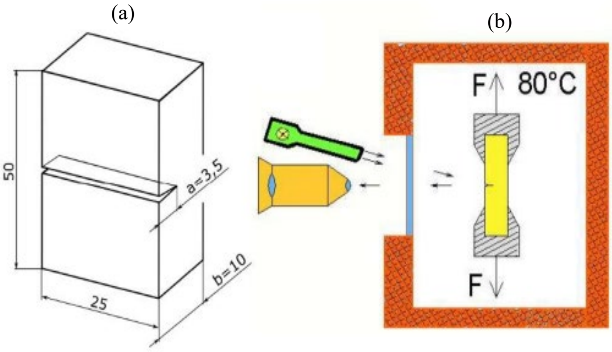

Figure 1. (a) Specimen prepared for PENT test, (b) test sequence diagram PENT realized in the laboratory (Nezbedova et al. 2009).

$$t_f = t_{PENT} \cdot \left[\frac{0.468}{K_I}\right]^m \cdot Exp\left[\left(\frac{Q}{R}\right)\left(\frac{1}{T}-\frac{1}{353}\right)\right] \quad (1)$$

The factors of the overhead equation are achieved for a characteristic sample PENT (ASTM F1473-07, 2007):

t_{PENT}: service life in hours during a PENT test, [100-500] hours,

K_I: stress intensity factor, $MPa.m^{1/2}$,

$K_{PENT} = \sigma_{PENT} \cdot \sqrt{\pi \cdot a_{PENT}} \cdot Y_{PENT} = 2.4 \cdot \sqrt{3.14 \cdot 3.5} \cdot 3.3 = 0.468 MPa \cdot m^{1/2}$,
m: constant material [2.5-4], m = 3 is commonly used,
Q: Activation energy [85000-110000] J/mol,
R: constant of perfect gasses 8.31446 J .mol^{-1}.K^{-1},
T: absolute temperature in Kelvin, T<353K (80°C),

3. Reliability analysis based on PENT model

The reliability analysis must include describing a function of HDPE pipe performance or what is called "state of the system" designated by *G(Xj)*, where *Xj* are the random variables of the system. We select it to correspond to the conservative security boundary demarcated through the transformation among the lifetime t_f based on PENT model (Equation 2) and the estimated lifespan in the literature equal to 50 years. The frontier state function which discrete the safe area, *G(Xj)>0*, from the failure area, *G(Xj)<0*, is measured to assess the reliability index. Consequently, the limit state function used is given in Equation 2:

$$G = 50 - t_{PENT} \cdot \left[\frac{0.468}{K_I}\right]^m \cdot Exp\left[\left(\frac{Q}{R}\right)\left(\frac{1}{T} - \frac{1}{353}\right)\right] \tag{2}$$

P_f failure probability is acquired through formulation (3); $P[G(X) \leq 0]$ is the probability operator and $\Phi(-\beta)$ is the cumulative Gaussian probability function. β corresponds to the probability of failure P_f.

$$P_f = P\left[G(X_i) \leq 0\right] = \phi(-\beta) \tag{3}$$

3.1 β function of the crack length 'a'

Liable to quality control procedures aimed at plastic pipe engineering, the occurrence of minor faults is probable to arise and even to be conventional for very low pressure solicitations. Hereafter, such defects are commonly current on HDPE tubes; however it should be implicit that for scopes pending 300 µm, pipe crack initiation could be ongoing which causes premature failure.

Figure 2 displays the evolution of reliability index as function of crack length a. However, the shape of the curve is similar to that observed in the case of K_{IC} (Alimi et al. 2017, Alimi et al. 2018). We note that for values of 100 µm <a <400 µm the reliability index is very small which distances us from the value of β close to 3.7272 recommended by the manufacturers.

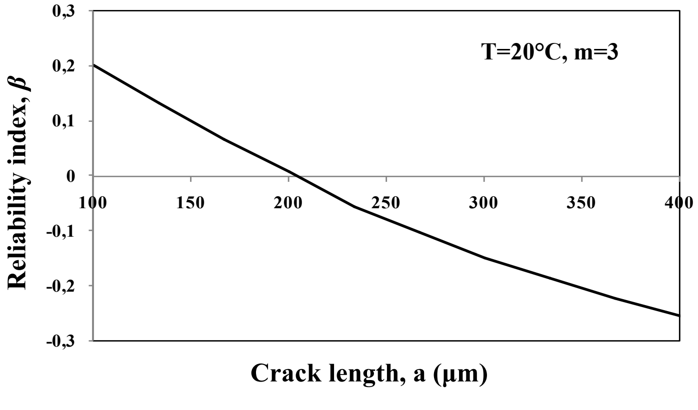

Figure 2. Reliability index β as a function of crack length a.

In Figure 3, we can find the disparity of β as a function of a at different service temperatures. This first result tells us that the values of β that may interest us would be at very small crack lengths. This implies that in order to have acceptable β values, the quality control must ensure fault sizes of less than 0.2 µm!. This condition is very difficult to achieve. Finally, to have sufficient β, it is necessary to improve the parameters influencing t_{PENT}. It is clear that for more severe conditions (T> 20 ° C), the β values degrade even more.

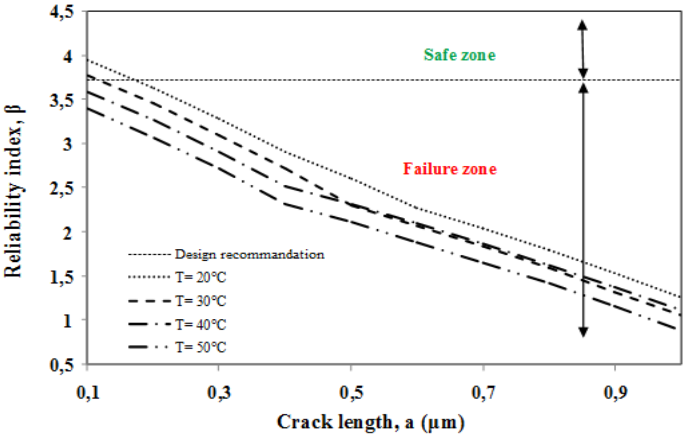

Figure 3. Reliability index *β* as function of crack length by dissimilar temperatures.

N. Brown calculated the life of polyethylene pipe (SDR 11) with a size defect equal to 0.14mm (140µm) using Equation 1. In its calculation, the temperature of the soil in which the pipes are buried is 10 ° C, m = 3, the stress intensity factor K_I is equal to 0.12 MPa.m$^{1/2}$. It takes into account the presence of residual tensile stresses equal to 2 MPa in the inner surface of the tube which are relaxed by the effect of temperature (80 ° C) and reduced to 50%, i.e a value close to 1 MPa. He found that the lifetime t_f = 118,000 t_{PENT} with 1 hour test PENT (ASTM F1473) represents the equivalent of 13 years of service. The coefficient 118.000 varies with applied stress and operating temperature (N. Brown, 2007).

3.2 *β* as a function of operating pressure 'p'

Figure 4 displays the evolution of the reliability index as function of the effective pressure at T=20°C and m constant material chosen equal to 3. We note that for values of 0.4 MPa <P <1 MPa, the reliability index is very small which distances us from the value of *β* close to 3.7272 recommended by the manufacturers.

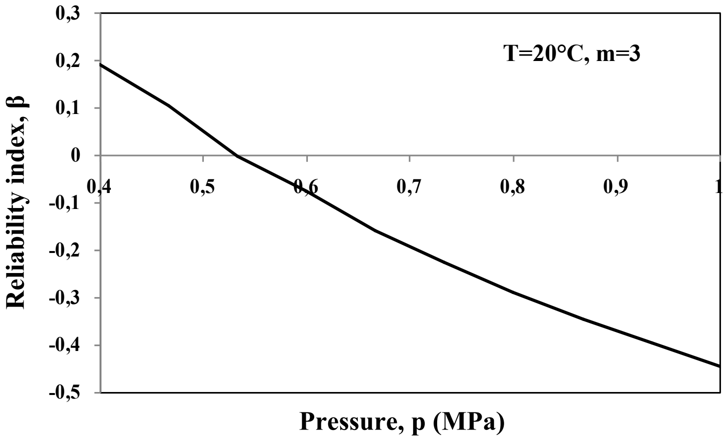

Figure 4. Reliability index *β* as function of effective pressure.

4. Conclusion

The main of this investigation was to establish the reliability index of a plastic pipe using a model of lifetime based on PENT approach. Although plastic pipe standards and their associated laboratory tests impose a safe structure service period for more than 50 years, reliability methods remain one secure way to evaluate the remaining structure's life. Based on PENT and reliability results, the following conclusions are made:

- Reliability of plastic pipes based on PENT is a decreasing function with crack length, and pressure.

- For values of 100 µm <a <400 µm the reliability index is very small which distances us from the value of β close to 3.7272 recommended by the manufacturers.

- The reliability index β varies according to the service temperature. At T = 20 ° C, β is close to the reliability index recommended by the manufacturers. When T increases the reliability index is degraded.

- This first result tells us that the values of β we may be interested in would be very small crack lengths. This implies that in order to have acceptable β values, the quality control must ensure fault sizes of less than 0.2 µm!. This condition is very difficult to achieve.

- Finally, to have sufficient β it is necessary to improve the parameters influencing t_{PENT}. It is clear that for more severe conditions (T> 20 ° C), the β values degrade even more.

- For the operating pressure, we note that for values of 0.4 MPa <P <1 MPa reliability index is very small which distances us from the value of β close to 3.7272 recommended by manufacturers.

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Biographies

Latifa Alimi is a researcher in the field of polymer materials, composites and biomaterials. She obtained her BS and MSc degrees in Mechanical Engineering from UBM Annaba. In 2016, she finalized a PhD degree in Mechanical Engineering at UBM Annaba (Algeria). Her research is mainly concerned with material design and degradation, industrial and technological applications. She worked specifically on piping systems to establish durability, environmental stress cracking, mechanical characterization and reliability. She is the author of several published articles and she participated in many conferences devoted to advanced materials.

Kamel Chaoui is a research professor who works in several fields such as: Industrial processes, Mechanics and Characterization of Materials, Sizing thermal and pressure equipment, Protection of distribution networks, Management (Quality, Environment, Technological Resources and Maintenance), Diagnostics and Technical Expertise, Industrial Risks, Methodology of Research, Standards and standardization, Impact studies of materials on environment and biodiversity, University-Business Relations. In 1998 he obtained the Diploma of Consultant, Quality Management (PME), PEM / GTZ Germany. In 1989, PhD Macromolecular Science and Polymer Engineering, Case Western Reserve Univ., Cleveland, Ohio, USA. 1986, Master's of Science, Engineering Mechanics, Case Western Reserve Univ., Cleveland, Ohio, USA. 1983- State Engineer, Option: Transport and Distribution of Natural Gas (TDG), Institute Algerian Petroleum (IAP), School of Engineers (EI), Boumerdès, Algeria.

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