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# PROBABILISTIC DESIGN FACTORS FOR PIPES USED FOR HYDROGEN TRANSPORT

Kuk Mijim J, Pluvinage G\*, Capelle J, Azari Z, Benamara M  
LEM3 Université de Lorraine, \* FM.C Silly sur Nied

## Abstract

Probabilistic design factors for pipes used for hydrogen transport are proposed for 3 locations: urban, peri-urban and rural areas.

The used method involves a risk equation defined as the product of probability of leakage after failure, probability to have a gas flow greater than a prescribed value, probability of ignition, probability of lethal effects greater than a threshold value and probability of the presence of a person corrected by an environment factor and a risk reduction coefficient. The results obtained are less conservative than the deterministic values provided by ASME code.

**Key words** : pipes, design factor, probability, hydrogen transport

## 1. INTRODUCTION

Hydrogen economy considers hydrogen as a substantial fraction of a country's energy and services. This could happen in the future if hydrogen can be produced from domestic energy sources economically and in an environmental-friendly manner. Fuel cell vehicles are now technically mature and potentially affordable and can gain market share in competition with conventional power generation sources and transportation vehicles. This would reduce dependence on oil and coal as the major sources of energy and improved environmental quality through lower carbon emissions. Many technical, social, and policy challenges must be overcome to ensure the transition to such economy can take place. Hydrogen is used as a sustainable energy carrier for electric fuel cell vehicles (EFCV) and as a means of storing renewable energy. Hydrogen can also be used as fuel in stationary fuel cell systems for buildings, emergency power or distributed generation.

Hydrogen transport is generally made by pipelines. This solution is preferable over transport on the road by truck for safety reasons. Pure hydrogen is transported via pipelines. The introduction of hydrogen into the existing pipeline network has been proposed as a mode of transporting renewable energy from the production site to the consumers systems such as large wind farms. If mixed with relatively low concentration about less than 5% -15% of hydrogen by volume, this solution is viable on condition that the risks associated with the use of the gas mixture in end-use devices (such as household appliances), general public safety or the sustainability and integrity of the existing network of pipelines are not significantly affected. Any introduction of a hydrogen mixture would require modifications to the design, monitoring and maintenance practices of existing networks.

When comparing to the risk posed by natural gas, pure or blended hydrogen transport related component induces the following problems:

- hydrogen presents a wider range of flammable concentration which increase the likelihood of ignition and resulting damage;
- durability of metallic pipes is affected when exposed to hydrogen for long periods, in particular with higher concentration hydrogen in operating at high pressure by a phenomenon so-called hydrogen embrittlement. This effect strongly depends on steel strength and must be assessed on a case-by-case basis. However, the pipe steels in transport systems are mainly made of medium resistance steels, typically API 5L X52, which are quite sensitive to embrittlement induced by hydrogen under normal operating conditions.

Pipeline design ensures that failure occurs when the strength capacity of the pipe steel is exceeded. This consists of verifying that the membrane stress does not exceed the admissible stress define as the material strength divided by a safety factor. In codes, this approach is slightly different as the acceptable service pressure has to be lower than the value of the maximum allowable operating pressure (MAOP). Pipe MAOP have received attention mainly in codes [1-2]. A particular attention on pipe MAOP has been paid in case butt welds, saddle, cones, spheres and formed heads[3-8].

The calculation of the MAOP is based on the so-called “boilermaker formula” which introduces a design factor  $f_0$  given by the code.

Different values of design factor are suggested according to different location (urban, semi-urban or rural areas). These values are estimated by experts and are known to belong to deterministic approach. New trend of safety is based on an allowable probability of risk as a compromise between safety and cost.

For pipes used for hydrogen transport, the highest value of admissible risk is a probability of occurrence of  $P_r = 10^{-5}$ .

In general, the probability of an incident and the human, economic or societal consequences of this particular incident are combined into an overall risk factor. The risk associated with pipeline for hydrogen transport is determined using the following general equation:

*Risk = Frequency of pipeline failure \* probability of flow lesser than a critical value, \* probability of ignition \* probability of the presence of a person \* probability of lethal effects greater than a threshold value.*

When the aforementioned risk is defined as an individual and human risk, the result is the probability of a person becoming a victim in a year. Global risk is therefore the product of all failures and consequences (per year). It is expressed by the probability that a point located near a pipe and at a known distance could be exposed until it reaches intensity greater than a reference level.

The aim of this paper is to determine the design factor for pipes used for pure or blended hydrogen for 3 different locations: rural, peri-urban and urban areas. For each case, an admissible risk probability of  $10^{-5}$  is assumed. The design factor is therefore computed using the following risk probability equation:

$$P_r (\text{Risk}) = P_r (L) * Pr(Q) * P_r (I) * Pr (LE) * P_r (\text{pers}) * L * C_{ev} * C_{rr} \quad (1)$$

- $P_r (L)$  probability of leakage after failure,
- $P_r (Q)$  probability of gas flow lower than prescribed value
- $P_r (I)$  probability of ignition,
- $P_r (LE)$  probability of lethal effects greater than a threshold value,
- $P_r (\text{pers})$  probability of the presence of a person,
- $L$  length of the pipeline taken into account,
- $C_{ev}$  coefficient taking into account the location of the pipeline,
- $C_{rr}$  risk reduction factor taking into account risk reduction measures.

Here, one proposes to compute the risk associated to overcome the maximum allowable working pressure (MAOP) in a smooth pipe. Probabilistic design factor  $f_{0,pro}$  associated with 3 locations (rural, urban and peri-urban areas) are computed and compared with deterministic design factor  $f_{0,det}$

## 2.MATERIAL

In this study, we consider API 5L X60 steel pipe which is a micro-alloyed steel in relation to its content of alloying elements. Table 1 shows the chemical composition of this steel. It is composed of 0.16% carbon and several alloying elements, such as titanium and niobium.

Table 1: Chemical composition of API 5L X60 steel

Additives	C	Si	Mn	P	S	V	Nb	Ti
%	0.16	0.45	1.65	0.020	0.010	0.07	0.05	0.04

Its standard mechanical properties are as follow: yield stress  $\sigma_y$  : 510 MPa, ultimate strength  $\sigma_{ul}$  610 MPa and elongation at failure  $A\% = 21\%$

Several tensile tests (10) have been performed in order to have the yield stress statistical distribution. Hydrogen embrittlement has been made using cathodic charging [12] during 1 week (165 hours); Assuming that the statistical distribution is Normal by considering their skewness and kurtosis values, the following results are obtained, Table 2.

In order to evaluate the probability of gas flow greater than a critical value  $P_r (Q)$ , it is necessary to calculate the flow emanating from a pipe aperture. The size of the aperture needs to be identified. To identify the aperture, a method base on the critical Crack Tip Opening Angle (CTOA) is used [13]

The CTOA  $\Psi$  is defined as the angle between the crack faces of a growing crack. Practically, its definition is based on crack tip opening displacement  $\delta$  at a distance  $d$  of the order of 1 mm (Fig. 1).

$$\Psi = \arctg \left( \frac{\delta}{2d} \right) \quad (2)$$

Table 2 : Statistical distribution parameters of yield stress of API5L X52

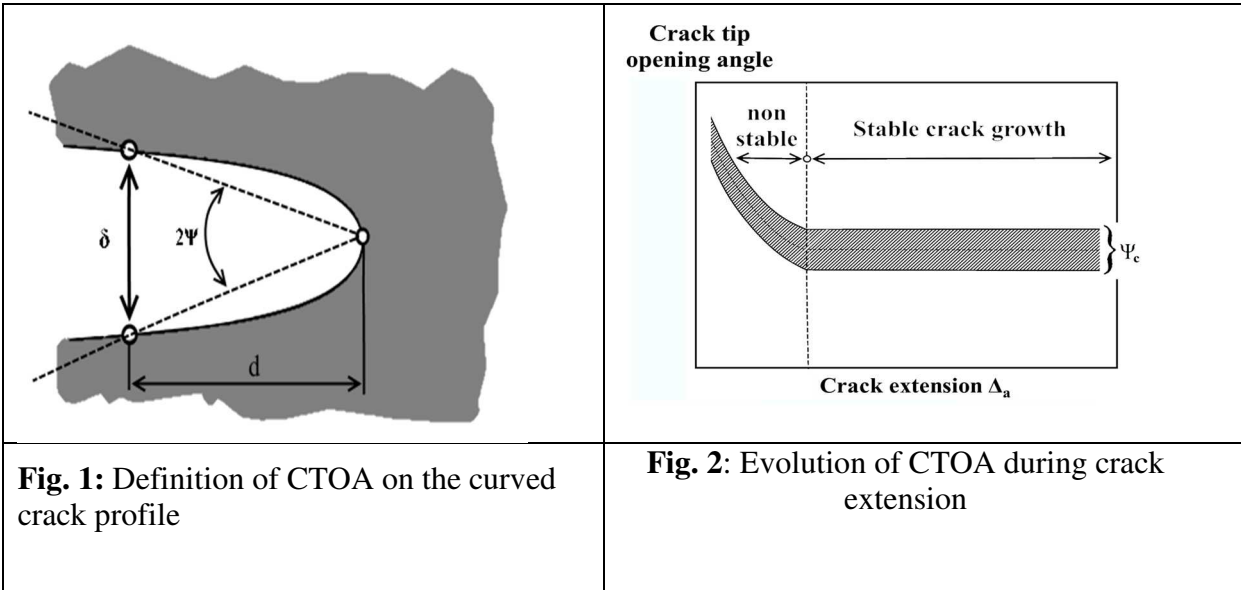
Physical parameters	Values			
	Mean, $\mu$	Standard -deviation, $\sigma$	Skewness	Kurtosis
Yield stress without HE	511 MPa	25.54 MPa	-0.007	3.01
Yield stress With HE	515 MPa	28.01 MPa	-0.008	2.95

Conditions of stable crack growth require that the rate of change of the crack driving force  $\delta_R$  with increasing crack length  $\Delta a$  to be smaller than the increase of crack growth resistance expressed in terms of crack opening displacement  $\delta$  :

$$\frac{d\delta}{da} \leq \frac{d\delta_R}{da} \tag{3}$$

It can be seen that on the R curve  $\delta_R = f(a)$  that the left term in (3) is precisely the CTOA that is constant in the linear part of the R curve (Fig. 2).

$$\frac{d\delta_R}{da} = CTOA \tag{4}$$



Gas pipeline fracture initiation is usually followed by extended running crack propagation. This occurs when driving force energy, caused by internal pipe pressure, overcomes the crack propagation resistance.

Conditions for crack propagation or arrest are given by a coupled fluid-structure problem. In terms of a limit state design, the arrest pressure can be predicted by solving equation (5) between the fracture resistance and component stress, which depend on the pipeline dimensions, internal pressure and material strength.

$$\langle \sigma_{ij}(p) \rangle = \langle \sigma_{ij,c}(p_{ar}) \rangle \quad (5)$$

where  $p_{ar}$  is arrest pressure. Condition of arrest can be transformed by the new following condition:

$$CTOA(p) = CTOA_c(p_{ar}) \quad (6)$$

where CTOA is the crack tip opening angle induced by the current pressure and  $CTOA_c$ , the fracture resistance. For API 5L X60 steel, a value of  $CTOA_c = 13.7^\circ$  is obtained using camera method described in [13]. This value is in agreement with value given by [14].

### 3. LEAK PROBABILITY $P_R(L)$

Leak probability is calculated according to the following criterion: leak is considered to happen when the service pressure  $p_s$  exceeds the Maximum Admissible Operating Pressure (MAOP).

$$P_s \geq MAOP \quad (7)$$

Maximum Admissible Operating Pressure is based on the so-called boilermaker formula:

$$MAOP = \frac{\sigma_y \cdot f_0 \cdot t}{R} \quad (8)$$

Where  $\sigma_y$  is the yield stress,  $t$  is thickness and  $R$  is radius of the pipe.  $f_0$  is the so-called design factor. A more detailed formula is given in [10] which involves the efficiency of the weld joint material quality factor, mechanical correction (thread or groove depth). Thickness must take into account future losses by corrosion and coefficient YB31 of the ASME B31 piping code. In this study, only equation 8 is being used. The design factor  $f_0$  is given by standard [15].

Table 3: Values of the design factor  $f_0$  and the associated safety factor  $f_s$  depending on the environment of the pipeline for natural gas [15].

location	Design factor $f_0$	Safety factor $f_s$
Rural area	0.73	1.37
Peri-urban area	0.6	1.67
Urban area	0.4	2.5

In Table 3 are reported the values of the design factor  $f_0$  and the associated safety factor  $f_s$  depending on the location of a pipeline used for natural gas transportation. Three design factors are defined and are shown in the following table. The safety factor  $f_s$  is defined as the inverse of the design factor and are also reported in this table.

The rural area includes an undeveloped area and an isolated area with a detached house, farm and livestock buildings.

The peri-urban environment includes areas with a single-detached house and farm housing and individual leisure buildings, with their necessary infrastructure.

The urbanized area covers a built-up area of one or more collective and individual residential houses, public utility installations, heavy traffic lanes and a developed underground network, such as water piping systems, systems sewers, heat distribution networks, gas networks, electricity, telecommunications as well as streets, roads and mining sites. Yield stress distribution is determined from 10 tensile tests carried out in the presence of hydrogen while the variation in the thicknesses  $t$  and in pipe internal radius  $R$  are determined from their minimum and maximum tolerances [15]. In this study, tolerances are obtained by the “3 standard deviations rule”. The three stochastic measures  $\sigma_y$ ,  $t$  and  $D = 2R$  will serve as input variables for the probability calculation which will be performed by the Monte Carlo method.

The Monte Carlo method is a computerized mathematical technique allowing risk to be taken into account in decision-making and is used in various fields such as finance, research and development and production. It calculates and recalculates the results according to, each time, a set of random values associated with the input variables [16]. Depending on the number of uncertainties and the ranges specified to represent them, a Monte Carlo simulation may involve, to be complete, thousands or even tens of thousands of calculations and re-calculations. For each input variable, its distribution parameters as well as its type of distribution law are indicated in Table 4.

Table 4: Distribution parameters and distribution law associated with each input variable

Variable	Mean $\mu$	Standard deviation, $s$	Skewness	Kurtosis	Distribution law
Yield stress	515.4 MPa	28.89 MPa	-0.007	3.00	Normal
Thickness	5.2 mm	0.24 mm	-0.0029	2.99	Normal
Diameter	314 mm	0.79 mm	-0.00076	3.00	Normal
MAOP	17.07 MPa	1.24MPa	0.10	3.01	Normal

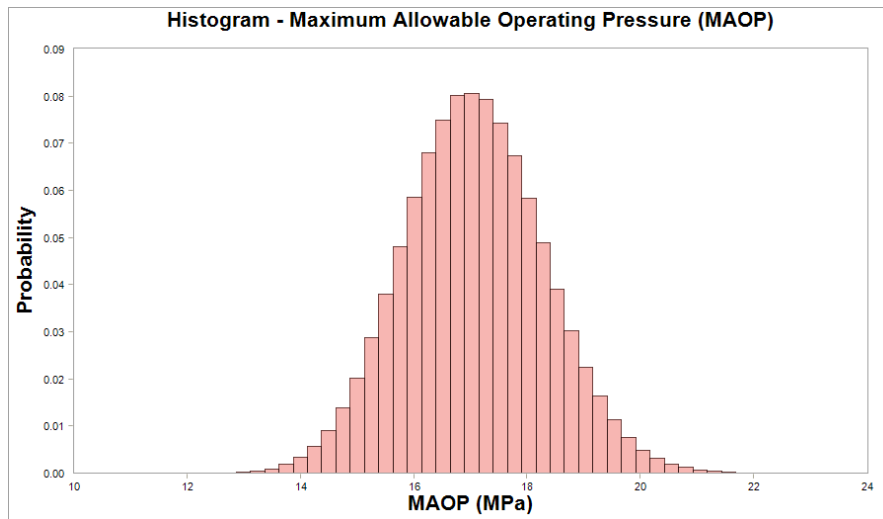


Fig.3 : Distribution of the probability density versus MAOP.  
Steel API 5L X60 . Pipe thickness 5.2 mm Pipe diameter 314 mm

First, the four main parameters of a distribution such as the mean, the standard deviation, the flattening and symmetry coefficients are compared in order to test the symmetry and the distortion of this distribution. According to Table 4, a positive skewness value indicates that the data set is skewed to the right i.e. the mean is greater than the median. The kurtosis is also greater than zero, which indicates that the central peak is higher and sharper than a normal distribution. In order to test whether the character of this sample can be approximated by a known or ideal probability law, the Kolmogorov-Smirnov test is carried out to compare this distribution with a theoretical distribution (values taken as mean and standard deviation are the ones indicated in Table 4).

This test compares the data obtained with a known or theoretical distribution, in this study, normal or the log-normal law. The parameters of the test are as follows:

- $D_{KS}$ : the biggest difference between the values from the actual distribution and the theoretical (or ideal) distribution
- $\alpha$ : risk of error (fixed at 5% or 0.05)
- $P_r$ : probability which measures the degree of certainty with which it is possible to invalidate the distribution hypothesis.

In order to determine whether, for example, a distribution follows a normal distribution, the value of  $P_r$  must be compared with the risk of error,  $\alpha$ . If  $P_r$  is less than  $\alpha$ , it is unlikely that the distribution follows a normal distribution and in this case, the assumption  $H_0$  can be rejected. On the contrary, if  $P_r$  is greater than  $\alpha$ , it is not possible to reject  $H_0$ .

For the MAOP distribution, two goodness-of-fit tests were carried out one for the Normal distribution and the other Log-normal distribution. Results of which are indicated in Table 5. When comparing  $D_{KS}$  value, it will be more precise to consider that the distribution approaches as a Normal distribution than a Log-normal distribution.



Table 5: The results of the Kolmogorov-Smirnov test for the normal distribution and the log-normal distribution

Parameters	Distribution	
	Normal	Log-normal
$D_{KS}$	0.04	1
$\alpha$	0.05	0,05
$P_r$	< 0.0001	< 0.0001

A curve following a normal distribution centered around the mean i.e. the mean and the median are equal. Results indicates that the mean (17.07 MPa) and the median (17.05 MPa) differ by 0.1%. For simplification purposes, we assume that the curve is almost symmetrical and this distribution will be considered as a Normal distribution.

#### Design factor by probabilistic approach

Assuming that the  $P_r$  (risk) is fixed at  $10^{-5}$  for the 3 locations, the probability of leak risk  $P_r(L)$  could be calculated when all 7 terms in equation 1 have been defined. Each MAOP associated to different location is computed by finding the correspondence between the value of  $P_r(L)$  with the cumulative frequency distribution obtained from the Monte Carlo simulation. Table 6 shows the values of MAOP for each location.

Table 6: MAOP and leak risk probability associated with location

Location	Rural area	Peri-urban area	Urban area
$P_r(L)$	$1.25*10^{-4}$	$6.67*10^{-6}$	$3.33*10^{-6}$
MAOP (MPa)	12.5	11.7	11.5

The safety factor are calculated using the following formula :

$$f_{0,prob,MAOP} = \frac{MAOP}{P_{r0,5}} \quad (9)$$

$$MAOP < P_{r0,5} \text{ with } P_{r0,5} : \text{Median} \quad (10)$$

$$f_s = \frac{1}{f_{0,prob,MAOP}} \quad (11)$$

The values of  $f_{0,prob}$  remains constant however the number of population in the location increases, as shown in Table 7

Table 7: values of MAOP design and safety factor associated with location

Location	Rural area	Peri-urban area	Urban area
$f_{0,prob,MAOP}$	0.73	0.68	0.67
$f_{s,prob, MAOP}$	1.36	1.45	1.48

#### 4.GAS FLOW RATE EMANATING FROM HOLE AND PROBABILITY OF FLOW RATE Pr(Q)

The value of the gas flow passing through a hole caused by pipe failure is related to the size of the breach. In order to obtain the breach size, Finite Element Method has been use in order to describe the phenomenon of crack arrest and to identify its dimensions i.e. length 2c and width 2a assuming that its shape is elliptical. Failure emanates from a pipe defect at the service pressure (55 bars in this study) and propagates in the intact pipe at constant service pressure.

Crack arrest criterion is given by equation 6 based on Crack Tip Opening Angle CTOA. It is described in §2 and more widely in [13]. The pipe's dimensions are : diameter 315 mm and thickness 5.2 mm. For the steel pipe API X60, the critical value of CTOA is:  $CTOA_c = 13.7^\circ$ . The stress-strain behaviour of the material is assumed to be elasto-plastic with strain-hardening and described in [12]. Figure 4 gives a description of the breach obtained by modelling the crack arrest phenomenon. The length of the breach is 2c :~400 mm and the width 2a :~20 mm.

The gas flow is computed by an analytical method. The pipe pressure is assumed to be constant despite the presence of a leak and the gas flow is considered supersonic.

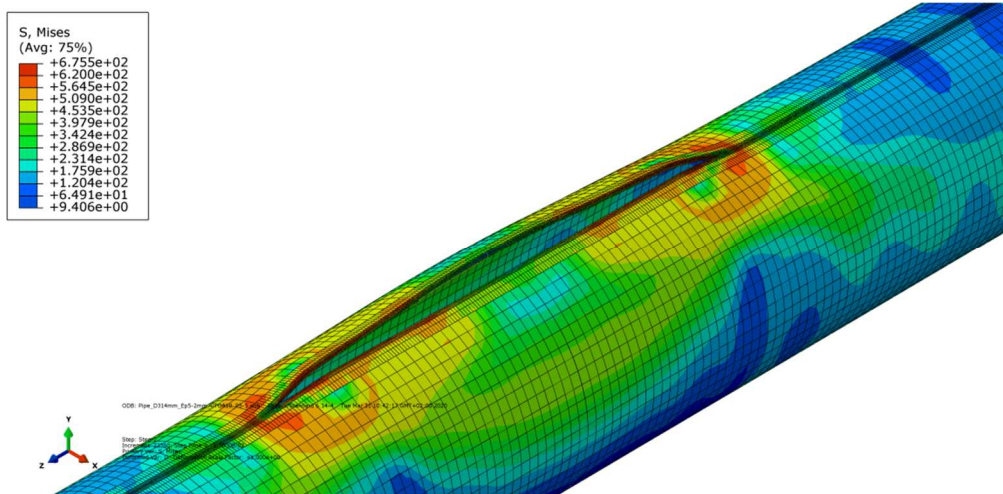


Fig.4: breach obtained by the burst of a pipe made in steel API 5L X60, diameter 315 mm and thickness 5.2 mm with method described in [13].

For analytical method, the gas leaking from a small hole behaves like an ideal gas and the leak rate can be calculated from equ.12 [17]:

$$q = pS \sqrt{\frac{2nM}{(n-1)GT} * \left[ \left( \frac{p_0}{p} \right)^{\frac{n}{2}} - \left( \frac{p_0}{p} \right)^{\frac{n+1}{n}} \right]} \quad (9)$$

with

q: flow rate of the leak in kg / s

p: internal pressure in Pa (5500000 Pa)

S: crack area in m<sup>2</sup> (0.025)

M: molar mass of hydrogen in kg / mol ( 0.002016)

G: ideal gas constant J / (mol.K, (8.314)

T: gas temperature in the pipe (293 K)

p<sub>0</sub>: atmospheric pressure in Pa (101325)

n: adiabatic coefficient of hydrogen (1.4)

With the above-mentioned value the leak rate, q is equal to 15.83 kg / s

## 5. PROBABILITY OF IGNITION P<sub>r</sub> (I)

On pipe carrying flammable, combustible or toxic products, a leak is considered to be originated from a breach. For our case, the leak origin is an ellipsoidal crack which has the dimension length 2c and width 2a. The crack length is defined from the condition of crack arrest given by the CTOA criterion and the width by the associated crack opening displacement at the middle of the crack.

According to BEVI [18], INERIS [19] and the Canvey report [20], the flow rate of a leak has an influence on the probability of immediate ignition. The values of these probabilities are indicated in Table 8.

Table 8: Probability of ignition according to BEVI [18], INERIS [19] and Canvey report [20],

	Flow rate, Q (kg/s)	Probability of ignition
BEVI [18]	<10	0.2
	10-100	0.5
	>100	0.7
INERIS [19]	>10	1
	1-10	1
	<1	0.1
Canvey [20]	< 1	0.01
	1-50	0.03
	>50	0.08

GESIP [21] proposes probability values according to the size of the breach, i.e. a small breach ( $\leq 12$  mm) with a probability of 0.59 or 1 for the other breaches.

Values proposed by INERIS are larger than those of BEVI. For leakage rate less than 10 kg / s, BEVI proposes a probability of ignition of 0.2 while INERIS proposes a value of 1, which is 5

times higher. However, BEVI offers the widest range of ignition probability values, ranging from below 10 kg/s to over 100 kg/s.

Suppose that two leakage values are considered i.e. 10 kg / s and 100 kg / s, according to BEVI, the flow rate 10 kg / s corresponds to a probability of ignition of 0.2 while a flow rate of 100 kg / s corresponds to a probability value of 0.7. For a leak with a flow rate between 10 kg / s and 100 kg / s, it is therefore possible to establish a linear interpolation according to the two limit values of probability of ignition cited above according to BEVI. The probabilities proposed in the Canvey report are lower compared to those of INERIS.

Based on the leak rate of 16 kg/s calculated based on equation 12, a probability of 0.5 suggested by BEVI [18] is taken into account and the upper limit of 100 kg/s is fixed as the reference value of leak rate.

## 6. RISK REDUCTION COEFFICIENT ( $C_{rr}$ )

The pipeline carrying gas is often buried or exposed to the open air. The work of monitoring or maintaining the pipeline may sometimes result in pipeline-related incidents, for example rupture. Statistics [22] indicate that the risk factor "Works by nearby third parties (external aggressions and accidental stinging)" is responsible for more than 56% of the accidents recorded on the transport pipeline network. Consequently, a set of preventive measures is implemented to reduce this factor of third party work, amongst which a risk reduction coefficient making it possible to assess the effectiveness of the measures is integrated into the risk probability equation (equation 1). Table 9 shows some values of the risk reduction coefficients obtained from GESIP [22]. Certain values are suggested by experts while those obtained from HSE report 372/2001 and are estimated from pipeline failure frequency using PIPIN (PIPeline INtegrity model) software based on statistics taken from EGIG 1997 and BG Transco reports. [23]

Table 9 : Extract of risk reduction coefficient values,  $C_{rr}$  (or compensatory measure, EMC) from the GESIP report [22].

Compensatory actions	$C_{rr}$	Sources
Upper tube thickness > 11 to 15 mm	0.01	GDF Suez studies
Wire mesh easement strip with indication	0.01	Expert opinion
Concrete slab	0.05 à 0.01	HSE 372/2001
Reinforced marking	0.3	Expert opinion
Warning grid	0.6	HSE 372/2001
Permanent surveillance (camera...)	0.01	Expert opinion
Information/ Awareness	0.8 à 0.3	Expert opinion

Two limit values of the risk coefficient are used for this study : 0.01 for optimum protection and 1 for cases where compensatory measures are not imposed.

## 7. ENVIRONMENT COEFFICIENT ( $C_{ev}$ )

Gas network passes through different regions and altitudes which requires additional measures intended to reinforce the safety of the pipes. In the risk analysis, the environment around the pipeline has an influence on risk probability and it is translated as environment coefficient  $C_{ev}$ . This coefficient is greater than or less than 1 depending on the aggravating or improving nature of the environment. GESIP [22] proposes coefficients according different environments in Table 10.

Table 10: Coefficient taking into account the pipeline location according to GESIP [22]

Location of the pipeline	$C_{ev}$
Rural area (not urbanized) Population density: < 8 people / ha	0,8
Suburban or urban area	3
Standard parking	1
Confined space managed by an identified operator	0,1
Existing habitat and measure integrating information	0,05

In this study, three areas were defined i.e. rural, semi-urban and urban. The values of the environmental coefficient used are 0.8 for the rural area and 3 for both the semi-urban and urban areas.

## 8 PROBABILITY OF PRESENCE OF A PERSON, $P_r$ (PERS)

Dangerous phenomena resulting from a pipe leak can have serious consequences for persons in nearby area. Since the results depend on the substance properties and the transport conditions, the damage could extend over several meters or even several hundred meters [9]. The hazard study makes it possible to determine these effect areas and to define, if necessary, the risk reduction measures to be implemented.

INERIS [24] proposed delayed ignition probability values for a long-term (greater than 30 seconds) and short-term (less than 30 seconds) leak. These two values are identical for specific highly reactive gases (hydrogen, acetylene, acetylene oxide, etc.) and they are classified according to the duration of the presence of ATEX which is also assimilated to the presence of people around the installation of the pipeline.

4 classes are proposed noted A, B, C and D [25]:

- A: Absence of ignition sources
- B: "Classified ATEX" with the occasional presence of staff
- C: "ATEX classified" with a regular presence of personnel
- D: "Zone not classified ATEX" containing possible sources of ignition

Values of probability of presence of person,  $P_r$  (Pers) according to the 3 locations defined in our study i.e. rural, peri-urban and the urban areas are given in [25]. INERIS suggests : 0.1 associated with zone A where staffs are absent and 1 associated with zone C with regular

presence of staff. For the peri-urban area, which is located between these two extreme limits, we estimated the  $P_r$  (Pers) to be equal to 0.5. Table 11 summarizes selected values for  $P_r$  (Pers).

Table 11: Values of  $P_r$  (Pers) according to locations

	$P_r$ (Pers)
Rural area	0,1
Peri-urban area	0,5
Urban area	1

## 9. PROBABILITY OF LETAL EFFECT $P_R$ (LE)

Hydrogen has a large range of flammability in air (Table 10) and a low ignition energy. An atmosphere that is too rich or too poor in hydrogen cannot allow it to ignite or explode. Its main characteristics are shown in Table 12.

Table 12: Ignition and flammability of hydrogen

Auto-ignition temperature in air ( $^{\circ}$ C)	Flammability limit in air (% vol)	Minimum ignition energy (mJ )	Burning rate in air ( $m.s^{-1}$ )
585	4-75	0.02	2.7

A cloud of flammable gas is formed from a mixture of hydrogen and ambient air within a few seconds after hydrogen release. Due to its very high burning rate, this cloud could produce an explosion. It disperses quickly and can establish a quasi-stable gas jet. If the released gas ignites immediately, a torch-shape flame is produced. In the case of delayed ignition, an explosion of the gas cloud is possible.

### 9.1 Heat flux

If the source of a leak is a small hole and the fire is a flaming jet, the received heat flux at a certain distance from the fire source and per unit area, can be calculated as follows [26]:

$$Q = \frac{\gamma\tau q H_c}{4\pi r^2} \quad (13)$$

with:

Q: heat flux in  $W.m^{-2}$

$\gamma$ : radiation coefficient (0.2)

$\tau$ : atmospheric transmissivity (estimation: 0.95 [18] )

q: leakage rate in  $kg.s^{-1}$

$H_c$ : heat of combustion in  $J. kg^{-1}$  (for hydrogen: 141 584  $kJ.kg^{-1}$  [19])

r: radial distance between the fire and the place of interest

The flow rate, q can also be expressed by the effective gas release rate  $q_{ef}$  :

$$q_{ef} = 6,47 * 10^{-4} A_p \alpha p_0 * \max \left[ 0.3 ; \frac{1}{\sqrt{1+4,18.10^{-3} \alpha^2 (L)/D}} \right] \quad (14)$$

$\alpha$ : size of the dimensionless hole  $\alpha = \frac{A_h * C_D}{A_p}$ ,

$A_h$ : area of the leak in  $m^2$ ,  $A_p$ : pipe section in  $m^2$ ,

$C_D$ : rejection coefficient i.e. ratio between the actual discharge flow and the theoretical discharge,

$p_0$ : operating pressure in Pa ,

L: length of the pipe from the gas supply station to the point of fire in m

The flow value used in the calculation is  $100 \text{ kg}\cdot\text{s}^{-1}$  which corresponds to the reference value of leakage flow. The radial distance between the light and the place of interest, r is taken equal to the previously selected effect: 5 m. Therefore, the computed value of the heat flux is  $13.38 \text{ kW}\cdot\text{m}^2$ .

## 9.2 Explosion energy

After leak, the explosion can be confined (bursting of a flammable liquid tank) or unconfined also called UVCE (Unconfined Vapor Cloud Explosion) [20]. The effects of a UVCE explosion are essentially pressure effects like those caused by hydrogen. Two methods commonly used to assess the overpressure effect due to the explosion are the TNT equivalent method and the multi-energy method.

The TNT equivalent method consists in converting the potential energy of the explosive cloud into a mass of TNT equivalent, while the multi-energy method assimilates the explosion in a cloud to an explosion with hemispherical symmetry at constant flame speed. The explosion of the pipeline carrying hydrogen is classified as an unconfined explosion of the UVCE type.

The combustion energy is the energy released by the combustion reaction of a gas and oxygen in air and is calculated according to equ.15 :

$$E = \frac{q * t}{\rho * C_{\text{stoechio}}} * \Delta H \quad (15)$$

with:

E: combustion energy in J, q: leakage flow in  $\text{kg}\cdot\text{s}^{-1}$  (100),

t: ignition delay in s (30)

$\rho$ : gas density of in  $\text{kg}\cdot\text{m}^{-3}$  ( $5.17 \text{ kg}\cdot\text{m}^{-3}$  for gaseous hydrogen)

$C_{\text{stoechio}}$ : Stoichiometric concentration in% (in air, 29.5% [27])

$\Delta H$ : Hydrogen heat of combustion in  $\text{MJ}\cdot\text{m}^{-3}$  (59.2)

The ignition delay is generally 60 s However, the value retained is 30 s when considering hydrogen as a very reactive gas with a minimum ignition energy which is low.

The calculation gives an explosion energy,  $E = 59.2 \text{ MJ}$

### 9.3 Overpressure effect

In practice, the level of overpressure is given without justification or extensive demonstration by resorting to an expert opinion as feedback based on accidentology. However, this taking into account, when it is made, remains purely qualitative and it is often difficult to justify precisely this choice since it is not based on any calculation. The following method consists in reading the chart (Figure 5) in order to determine the overpressure value associated with the chosen reduced distance of effect.

Calculation of the reduced distance corresponding to an effect distance 5m for the 3 locations : rural, semi-urban and urban areas.

$$\bar{R} = \frac{R}{\left(\frac{E}{p_0}\right)^{\frac{1}{3}}} \quad (16)$$

with

$\bar{R}$  Reduced distance in m

R: Distance between the point considered and the explosion center in m

E: Combustion energy in J (obtained from [Equation 14], 59.20MJ)

$p_0$ : Atmospheric pressure in Pa (101325 Pa)

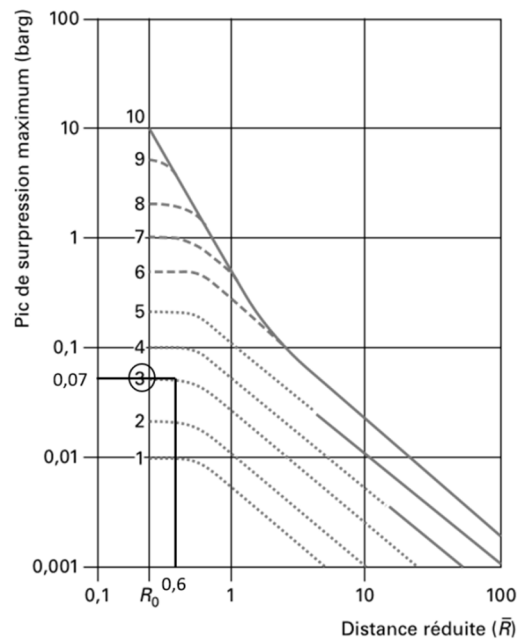


Fig.5 :Multi-Energy method blast chart used to determine the overpressure due to thermal explosion

The reduced distance is used to find the explosion overpressure value,  $\Delta P$  which can be calculated using

$$p_s = \Delta P / p_0 \quad (17)$$

with:

$p_s$ : Maximum overpressure in bar g (to be read on the vertical axis in Figure 5.

$\Delta P$ : Overpressure linked to the explosion in bar,  $p_0$ : Atmospheric pressure in bar

The reduced distance is found as 0.47m and the overpressure is found Fig 5 as 7.57Kpa



#### 9.4 Lethal effect due to thermal combustion

In regulatory studies, three critical thresholds causing harmful effects on humans are used:

- Threshold for Irreversible Effects (SEI) corresponding to the zone of significant dangers for human life: 3 kW.m<sup>-2</sup> for thermal effects, 50 mbar for overpressure effects,
- Threshold of the first Lethal Effects (SEL) corresponding to the area of serious dangers for human life, 5 kW.m<sup>-2</sup> for thermal effects, 140 mbar for overpressure effects,
- Threshold for Significant Lethal Effects (SELS) corresponding to the zone of very serious dangers for human life, 8 kW.m<sup>-2</sup> for thermal effects, 200 mbar for overpressure effects [28].

The probability of death due to thermal effect can be estimated using a Probit function (Equation 18) and the probability of death, P<sub>death</sub> (Equation 19) proposed by Tsao & Perry [29]:

$$Pro = -12.8 + 2.56 \ln \left( Q^{\frac{4}{3}} t \right) \quad (18)$$

$$P_{\text{death}} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Pro} e^{-0.5s^2} ds \quad (19)$$

Q: heat flux in kW.m<sup>-2</sup> (8.56KW/m<sup>2</sup>), t: duration of exposure in s (30). Value of Probit for lethal thermal effect is 3.23 and the associated probability of death, P<sub>death</sub> = 0.04.

The probability of death due to overpressure effect can be estimated using a another Probit function (Equation 20) and the probability of death, P<sub>death</sub>(Equation 19) proposed by Eisenberg and al [30] :

$$Pro = -15.6 + 2.56 \ln (\Delta p) \quad (20)$$

Δp overpressure in Pa

Value of Probit for overpressure thermal effect is 1.63 and the probability of death is close to 0. Therefore, the lethal effect due to overpressure is not taken into account in this case.

## 10 .DISCUSSION

Recalling equation 1 defined at the beginning of this study,

$$P_r (\text{Risk}) = Pr (L) * Pr(Q) * P_r (I) * Pr (LE) * P_r (\text{pers}) * L * C_{ev} * C_{rr} \quad (21)$$

- P<sub>r</sub> (L) probability of leakage after failure,
- P<sub>r</sub> (Q) Probability to have a gas flow lower than a prescribed value
- P<sub>r</sub> (I) probability of ignition,
- P<sub>r</sub> (LE) probability of lethal effects greater than a threshold value,
- P<sub>r</sub> (pers) probability of the presence of a person,
- L length of the pipeline taken into account,
- C<sub>ev</sub> coefficient taking into account the location of the pipeline,
- C<sub>rr</sub> risk reduction factor taking into account risk reduction measures

Table 13 : Minimum, maximum and chosen valuesfor  $C_{ev}$ ,  $C_{rr}$ ,  $Pr(I)$ ,  $Pr(Q)$ ,  $Pr(EF)$

Terme	Mini	Maxi	Choix	Justification of choice
$C_{ev}$	0,8	3	0.8- 3	Depending on environment rural, peri-urban or urban areas
$C_{rr}$	0,01	1	1	No specific protection
$Pr(Q)$	0,2	0,5	0,5	0.5 corresponds to a flow ranging from 10 to 100 $kg.s^{-1}$ (computed flow rate is 16 $kg.s^{-1}$ )
$Pr(I)$	0,04	0,5	0,5	0.5 corresponds to probability of immediate inflammation
$Pr(EF)$	0	0,04	0,04	The probability of 0.04 is associated with lethal risk caused by thermal effect 0 corresponds to lethal risk emanating from overpressure effect.

$P_r(L)$  and are obtained  $Pr(Q)$  from calculation and include material parameters.  $P_r(I)$ ,  $P_r(LE)$ ,  $P_r(pers)$  are obtained by experts as well as  $C_{ev}$  and  $C_{rr}$ . Table 13 reports the minimum, maximum and chosen value for certain parameters. The choice is generally made using conservatism, which is commonly used in risk assessments.

Table 14 gives a summary of parameter values of equation 1 for the 3 locations (rural, peri-urban and urban areas). This table gives also the probability of leak  $P_r(L)$ , here leak is considered to happen when the service pressure  $p_s$  overcomes Maximum Allowable Operating Pressure MAOP and associated with a conventional probability of risk of  $10^{-5}$ .

This probability is generally recommended by codes as a compromise between safety and costs. This table gives also value of MAOP for the 3 locations, where the values are identical. The last line gives a round off value of design factor computed by probabilistic method  $f_{0,prob}$   
Table 14 summary of parameter values of equation 1 for the 3 locations (rural, peri-urban and urban areas).

Table 14 : summary of parameter values of equation 1 for the 3 locations

location	Rural area	Peri-urban area	Urban area
$P_r(\text{Risk})$	0.00001		
$L(\text{km})$	100		
$C_{rr}$	1		
$P_r(Q)$	0.5		
$P_r(I)$	0.5		
$P_r(EF)$	0.04		
$P_r(\text{Pers})$	0.1	0.5	1
$C_{ev}$	0.8	3	3
$P_r(L)$	$1.25 \cdot 10^{-4}$	$6.67 \cdot 10^{-6}$	$3.33 \cdot 10^{-6}$
MAOP (MPa)	12.5	11.7	11.5
$f_{0,prob}$	0.8	0.7	0.7

Table 15 shows a comparison between probabilistic design factor  $f_{0,prob}$  given by the present method and deterministic one  $f_{0,det}$  given by [1]. One notes that deterministic values are

more conservative and differs between the 3 locations. Unfortunately, no description was found in [9] which leads to such value of deterministic design factor.

However, definitive conclusion are limited due to the fact that this study has been made for a given pipe geometry and a particular pipe steel API 5L X60. Authors think that a larger study on other pipe geometry and other pipe steel could modify strongly the conclusion.

Table 15 probabilistic design factor  $f_{0,prob}$  deterministic design factor  $f_{0,det}$

	Rural area	Peri-urban area	Urban area
$f_{0,prob}$	0.8	0.7	0.7
$f_{0,det}$	0.6	0.5	0.4

Equation 1 is subjected to the COV of the pipe steels. Material properties have a strong influence on the design factor as one can see in Table16 and figure 6. The influence of COV of a range [0.05-0.20] on MAOP, indicates that for urban area, the MAOP decreases by 90% and design factor by 85%.

Table 16 : Influence of COV of yield stress on MAOP according to location

Location	COV	MAOP (MPa)	$f_{0,prob}$
Rural area	0,05	13,7	0,8
Peri-urban area		12,9	0,7
Urban area		12,8	0,7
Rural area	0,1	10,7	0,6
Peri-urban area		9,4	0,5
Rural area		9,1	0,5
Country area	0,15	7,7	0,4
Peri-urban area		5,7	0,3
Urban area		5,3	0,3
Rural area	0,2	4,5	0,2
Peri-urban area		1,9	0,1
Urban area		1,4	0,1

Modern steels manufactured with recent process have low inclusion content. The low scatter in mechanical properties with COV less than 0.1 ensures a design factor greater than 0.5. The European pipe networks include some very old part with low strength vintage steels with higher COV. Therefore, the usage of a uniform design factor for each part is problematic. Using the lower value for conservative reason induces an economical problem because with a low service pressure the gas flow is considerably reduced. If we assume that that the economical threshold for MAOP, called MAOP\* is 50 MPa, one cannot tolerate in the pipe networks, some part with vintage steels exhibiting a COV greater than 0.15, see Figure 6.

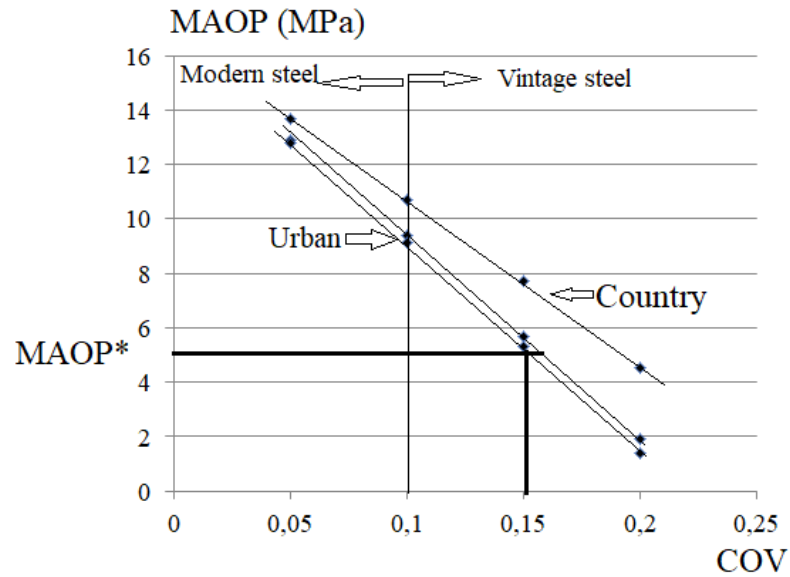


Fig.6 : Influence of COV of yield stress on MAOP according to environment, in the case of modern and vintage steels.

## 10. CONCLUSION

-The probabilistic design factor  $f_{0,prob}$  is calculated from a risk probability equation,  $P_r$  (Risk) which consists of 8 terms. This approach requires knowledge of material stochastic properties such as the yield stress and the crack extension resistance as  $CTOAc$  used for the probability of failure and the size of the breach under service pressure. Other probabilities values and coefficients assigned by expert opinion as proposed by INERIS and BEVI.

-This approach is based on assumption of a risk  $10^{-5}$  probability, this value is considered as a good compromise between safety and cost.

- 3 design factors have been computed according to each location, rural, semi-urban and urban areas. These design factors are identical to each other for the three locations. This might due to the number of terms in the risk probability equation which varies along with the environment, 2 terms viz. the coefficients taking into account the pipeline environment,  $C_{ev}$  and the probability of the presence of a person,  $P_r$  (Pers).

- Other coefficients such as the length of the pipe  $L$  and coefficient of risk reduction and other probabilities are identical for each location.

-The comparison between  $f_{0,prob}$  and deterministic values proposed by ASME noted as  $f_{0,det}$ , shows that  $f_{0,prob}$  are less conservative than ASME. However, it is difficult to justify these discrepancies because  $f_{0,det}$  are proposed by experts and no written reasoning was found behind the proposed values.

-Design factors influence on the one hand the choice of maximum admissible operating pressure and on the other hand the pipe thickness. Therefore, they have consequences on the cost of the pipelines and the amount of gas flow i.e. the profitability of the pipelines

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