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Semi-Probabilistic Approach to the Sizing of Hydrocarbons Canalisation

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Abstract: Actually as a conception rule and verification standards of the mechanical strength hydrocarbons transport pipelines, the deterministic formulation s used. The pipelines conception standards giving the sizing formulae and the acceptability criteria, as based on material strength formulae, on load limits and on ruin criteria such us flow and rupture limits without taking their aleatory character into account. A probabilistic approach to relate the conduit sizing to the risk of failure expressed in terms of probability which depends on distribution probabilities in the loads in the tube manufacturing dimensional tolerances and in the tube wall material strength. It does not, however, give sizing formulae such as deterministic formulae. It is this reason, that we try to develop formulae based on a semi probabilistic format which appear in a form analogous to deterministic formulae, but they incorporate elements of failure probability related to each of the quantities entering in the calculations.

Key words: Hydrocarbons canalisation, brobability

INTRODUCTION

The norms and standards concerned with pipeline construction are based on the strength theory called maximum normal stress theory. The determination of the tube wall thickness is made only in terms of the circumferential stresses due to the internal pressure action. The determination of the admissible stresses depends on the norm considered. In general, coefficients are introduced which take into account the nature of the area through which the conduit passes, the fabrication technology of the tubes, the corrosion … etc. A natural gas transportation conduit is made of huge number of tubes whose geometrical and strength characteristics are different from one tube to another in an aleatory manner. The deterministic formulae used in the norms dot not satisfy certain questions amongst which on can name, for example the relation ship between the calculated dimensions and failure probability.

A probabilistic approach permits to relate the sizing of the conduit to failure risk expressed in terms of probability, which depends on the load probability distributions, on dimensional tolerances during tube manufacturing and on tube wall material strength, but it does not provide explicit sizing formulae like deterministic formulae. This is why, one tries to develop a procedure based on semi-probabilistic format, which includes the failure probability elements related to each quantity contributing to the calculation.

Probabilistic approach: It is considered that the quantities used in the tube sizing formulae of a conduit are transient quantities. The mechanical behaviour of a tube is characterized by the bearing capacity R(t) and the load S(t). The tube good working probability for transient load and strength stresses is expressed by the relation ship[1].

$$P = \mathrm{Prob}\{R(t) \rangle S(t)\}$$

The intersection of the load and the bearing capacity curves Fig. 1 indicate the mutual action of the two probabilistic processes S and R. The probability for the tube strength to be bigger than the load for all its possible values is given by:

$$P = \int_0^\infty f_S(x)\left[1 - F_R(x)\right]dx, \text{ or } P = \int_0^\infty f_R(x)F_S(x)dx \quad (1)$$

Where f_R, f_S, F_R, F_S are the distribution densities and functions of the bearing capacity and of the load Fig. 2.

The load and the strength capacity of the elements of a conduit are determined by a set of perturbing factors, their distribution is considered as normal. Knowing their mathematical expectation m_R et m_S and their average quadratique deviationsσ, the good working probability is expressed by the relation ship[2]:

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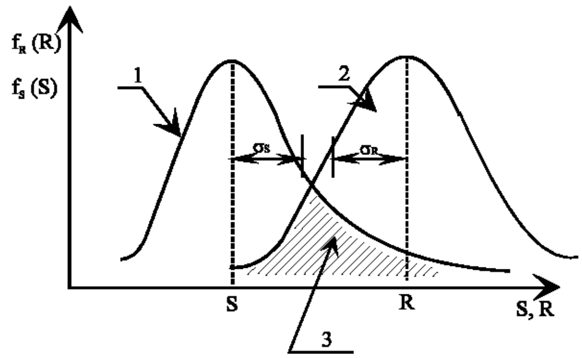

Fig. 1: Load and strength distributions f_S (S) and f_R (R) recovery

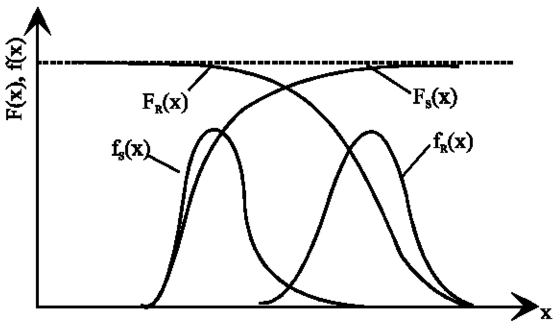

Fig. 2: Curves of load S and bearing capacity R repartition

$$P = F\left[\frac{m_R - m_S}{\sqrt{s_R^2 + s_S^2}}\right] \quad (2)$$

Introducing the non-rupture function: H = R – S, facilitates the calculation of the probability P. Expression (1) takes therefore the form Fig. 3[1]:

$$P = \int_0^\infty f_H(x)\,dx \quad (3)$$

Where f_H (x) is the distribution density of the transient quantity H, which is the combination of the transient quantities R and S.

For a normal distribution of the transient quantity H, the function P can be expressed by the relationship:

$$P = F\left(\frac{\bar{H}}{\sigma_H}\right) \quad (4)$$

Where $\bar{H}$ is the average value of the transient quantity H and σ_H is the average quadratique deviation of the transient quantity H.

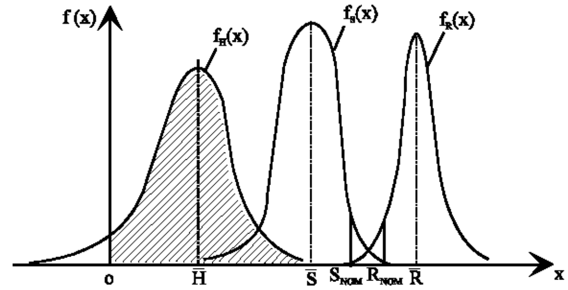

Fig. 3: Use for the non rupture function (S_{nomi} and R_{nomi} are the nominal values of the load and the bearing capacity)

For known distribution of R and S, the values of $\bar{H}$ and σ_H can be calculated by the formulae:

$$\bar{H} = \bar{R} - \bar{S}\,;\ \sigma_H^2 = \sigma_R^2 + \sigma_S^2$$

Where $\bar{R}$ and $\bar{S}$ are the average values of the transient quantities $\bar{R}$ and $\bar{S}$.

σ_S^2 and σ_R^2 are the variances of $\bar{R}$ and $\bar{S}$.

The inverse quantity of the variance coefficient V_H of the transient quantity H is called the safety characteristic[3]:

$$\gamma = \frac{1}{v_H} = \frac{\bar{H}}{S_H} = \frac{\bar{R} - \bar{S}}{\sqrt{\sigma_R^2 + \sigma_S^2}} \quad (5)$$

Semi-probabilistic approach: Introducing the variance coefficients of the charge and of the bearing capacity, the expression (5) can be written in the form:

$$\gamma = \frac{\bar{\eta} - 1}{v_R\sqrt{\eta^2 + k^2}} \quad (6)$$

$$\eta = \frac{\bar{R}}{\bar{S}}\ ;\ k = \frac{v_S}{v_R} \quad (7)$$

This ratio is called the reserve conventional coefficient. Depending on the tube material, the relationship between the quantities γ, V_S and V_R makes it possible to give a basis to the choice of the values of the overload and material homogeneity normative coefficients k_S and k_R.

$$k_S = 1 + \gamma v_S\ ,\ k_R = 1 - \gamma v_R \quad (8)$$

The over load coefficient k_S characterizes the load variability and the homogeneity coefficient k_R characterizes the material strength variability. The started coefficients are chosen starting from empirical distributions foe the corresponding factors and based on acquired experience in manufacture projection. One can also use the strength reserve coefficient η_R determining a given reliability P which is defined as the ratio of the smallest value of the strength capacity R_{min} over the greatest load S_{max}[4]:

$$\eta_R = \frac{R_{min}}{S_{max}} \geq 1$$

As calculation load S_{max}, one takes a load value above the average Fig. 4 obtained by calculation or by experiment. For the bearing capacity R_{min}, one takes the rupture load whose value is above the average, obtained by calculation or by experiment. In the statistical approach the calculation quantities R_{min} and S_{max} can be presented in form[2]:

$$S_{max} = \bar{S} + \alpha_S \sigma_S \ , \ R_{min} = \bar{R} - \alpha_R \sigma_R \qquad (9)$$

Where α_S are α_R the deviations of the quantities R_{min} and S_{max} with respect to their average values $\bar{R}$ and $\bar{S}$, expressed as a percentage of the average quadratic deviations σ_S^2 and σ_R^2.

For a normal distribution law of the transient variables S and R, the quantities α_S and α_R which are trust probability P^* quartiles, are determined during the choice of the calculation values R_{min} and S_{max}. In this way, it is shown that the strengthreserve can be formulated as:

$$\eta_R = \frac{\bar{R} - \alpha_R \sigma_R}{\bar{S} + \alpha_S \sigma_S} = \eta k_1 \qquad (10)$$

Where:

$$k_1 = \frac{1 - \alpha_R \ v_R}{1 + \alpha_S \ v_S} \qquad (11)$$

The rupture probability of the tube can be expressed by the specimen's rupture probability $\bar{P}$[5]:

$$\bar{P}^t = 1 - \left[1 - \bar{P}\right]^{V_t / V_e} \qquad (12)$$

Where V_t is the volume of the tube material

V_e is the volume of the test specimen

Introducing the coefficients of scale (k_e) and tube material homogeneity (k_h), the mathematical expectation of the rupture limit is determined by Fedossiev[6]:

$$\bar{R}^t = \bar{R}.k_e.k_h \qquad (13)$$

Where: $k_e = 1 - t_\xi V_R$ is the scale coefficient

V_r is the material strength coefficient depending on the specimen.

T_ξ is determined from the equation:

$$t_\xi = 0,5 + \Phi\left(t_{p^*}\right) = \left(0,5\right)^{V_e / V_t}$$

Laplace function

$$k_h = 1 - k_T^n V_{\sigma_R}^e \qquad (14)$$

Where k_h^∞ is the unilateral tolerated limit for a general set ($n = \infty$), determining how many average quadratic deviations it is necessary to subs tract from the mathematical expectation of the tube strength limit $\bar{R}^t$, for the rupture probability to be $\bar{P}(T)$. The tolerated limit k_T^∞ is given by the expression:

$$\Phi_0\left(k_T^\infty\right) = P(T) - 0,5$$

If the tube strength distribution parameters are determined from a specimen n, then k_T^∞ must be corrected according to the formulae[2]:

$$k_T^n = k_T^\infty \left(1 + \frac{t_q}{\sqrt{n}} - \frac{5t_q^2 + 10}{12n}\right) \qquad (15)$$

t_q is a parameter indicating that k^n_T is determined by expression (15) with a certain trust probability q. The value of t_q is determined from the expression:

$$\frac{1}{\sqrt{2\pi}} \int_{t_g}^{\infty} e^{-t^2/2} \ dt = 1 - q \qquad (16)$$

Taking the stress concentration in the tube walls into account, the bearing capacity reserve coefficient is given by the expression:

$$\bar{\eta}_t = \frac{1}{k_c} \cdot \frac{\bar{R}_t}{\bar{C}_{eq}} = \frac{\bar{\eta}}{k_c} \qquad (17)$$

Where K_C is the stress concentration coefficient.

$\bar{C}_{eq}$ is the mathematical expectation of the equivalent stresses in the tube walls.

Expression (15) can be written in the form:

$$\eta_t = \frac{m}{k_c} \cdot \eta_{0,2} \quad \text{where: } m = \frac{\bar{R}_t}{\bar{R}_{0,2}} \tag{18}$$

And

$$\bar{\eta}_{0,2} = \bar{R}^t_{0,2} / \bar{C}_{eq}$$

is the strength reserve coefficient according to the tube material lower flow limit.

To clarify the influence of the tube properties on the exploitation safety, the stress state under the action of the internal pressure is considered and using the specific potential energy hypothesis, the equivalent stress is given by the expression[6]:

$$C_{eq} = \sqrt{C_c^2 + C_l^2 - 2\mu C_l C_c} \tag{19}$$

where

$$C_C = \frac{P_S D}{2\delta}, \quad C_l = \mu \frac{P_S D}{2\delta} + \frac{ED}{2\rho} + \alpha l \Delta T$$

- p_S Internal pressure in the tube
- D Tube diameter
- δ Tube wall thickness
- μ Tube steel coefficient of Poisson
- α Thermal expansion coefficient
- ρ Tube flexion radius
- E Coefficient of longitudinal elasticity
- l Length of the tube considered

The normal tension in the tube welded joints is given by the expression[6]:

$$C_c = C_{eq} . k_c \cos^2 \alpha \tag{20}$$

Where α is the inclination angle of weld joint with respect to the tube generator.

It is important for the analysis to show the dependence of the tube working safety characteristic γ_t, in terms of the reserve coefficient $\bar{\eta}_{0,2}$, in the case of absence of correlation between the strength limit, the tube dimensions and non significant deviations of quantitie σ_R, D_{in}, δ and P_S s with respect of their mathematical expectation. The function H can be replaced by the linear relationship following decomposition into a Taylor series

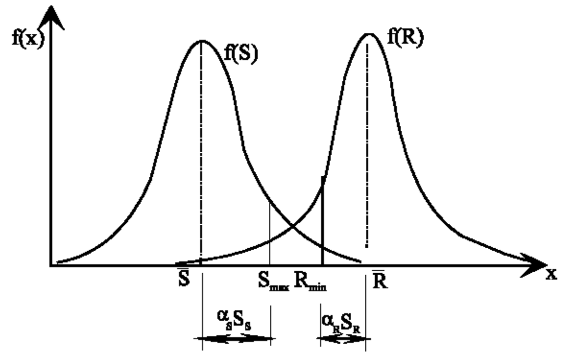

Fig. 4: Probabilistic presentation of the calculation load S_{max} and the calculation strength R_{min}

at the neighbour hood of the mathematical expectations of the transient quantities. In this case expression (6) takes the form:

$$\gamma_t = \frac{\bar{\eta}_{0,2} \cdot \kappa - 1}{\sqrt{\bar{\eta}_{0,2}^2 \kappa^2 \left(V_R^2 + V_\delta^2 + V_{D_{in}}^2 \right) + V_{C_N}^2}} \tag{21}$$

Where

$$\kappa = m . \frac{k_e . k_h}{k_c \cos^2 \alpha}$$

And V_x are the variance coefficients of indices x.

A tube begins to rupture, if the normal tension in the weld joint is:

$$C_N = R^t \tag{22}$$

Where:

$$C_c = C_{eq} . k_c \cos^2 \alpha$$

Where α is the angle made by the weld joint with the tube generator.

Supposing that the same equivalent stress is produced all along the length of the conduit section considered and bearing in mind that the defects will be different along the section, then the value of the safety characteristic will be different at the areas where the defects are located. If it is sought to insure the same level of safety over the section, then it is necessary to satisfy the condition:

$$\gamma_t(\bar{\eta}_t) \geq \gamma_{ad}\left[P(T)\right] \tag{23}$$

Where P (T) corresponds to a given reliability level of the study.

γ_{ad} [P (T)] is the safety characteristic corresponding to a reliability level P (T).

For a given stress concentration coefficient in the weld joints, the value of the bearing capacity reserve coefficient of the tube must satisfy the condition/

$$\bar{\eta}_t \geq \bar{\eta}_{ad} \qquad (24)$$

Where $\bar{\eta}_{ad}$ is the bearing capacity reserve corresponding to a given value of the safety characteristic γ_{ad} [P (T)].

RESULTS AND DISCUSSION

To verify the hypothesis used during the deduction of expression (21), stipulating that there is no correlation between the quantities σ_R D_{in} and P_S, the results of tests on specimens taken from X52 steel tubes of 1220 mm diameter and of different thicknesses have been analysed. Starting from the distributions of the specimen thickness and strength, the average of their values were determined and the regression are constructed Fig. 5. The regression lines obtained being perpendicular, it is concluded that $\bar{R}_t$ and δ are independent. On the other hand, the distribution of the diameter of the tubes depends mainly on their manufacturing process and is related neither to the thickness distribution, nor to the material properties. Lastly, the calculation parameters contributing to expression (19) are transient quantities mutually independent. On the other hand, the deviations of quantities σ_R D_{in}, δ and C_N are effectively small with respect to their mathematical expectations Table 1. In this way the linearization of the H function after decomposition in a Taylor series at the neighbour hood of the mathematical expectations of the transient quantities σ_R D_{in}, δ and C_N is justified.

To verify the hypothesis on the influence of the rupture strength scale factor (13), the tsts results on specimens taken from tubes of different thicknesses made of X52 steel and of dimensions 300×300xδ (in mm) have been processed. The treatment of the test results is presented in Fig. 6 and despite the small specimen volume; the departure of the curves for the greater wall thicknesses towards the left is perfectly visible. This shown the existence of an influence of the scale factor on the strength limit.

To show the feasibility and advantage of the semi probabilistic approach to the sizing of pipelines, a study was conducted on tubes of 1200 mm diameter, of 12 m

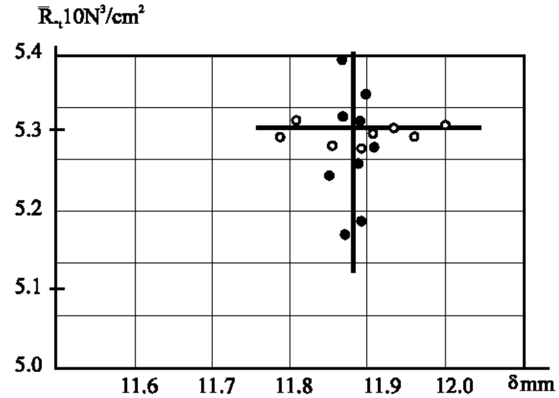

Fig. 5: Regression line of the deviation and the tube thickness and the strength limit

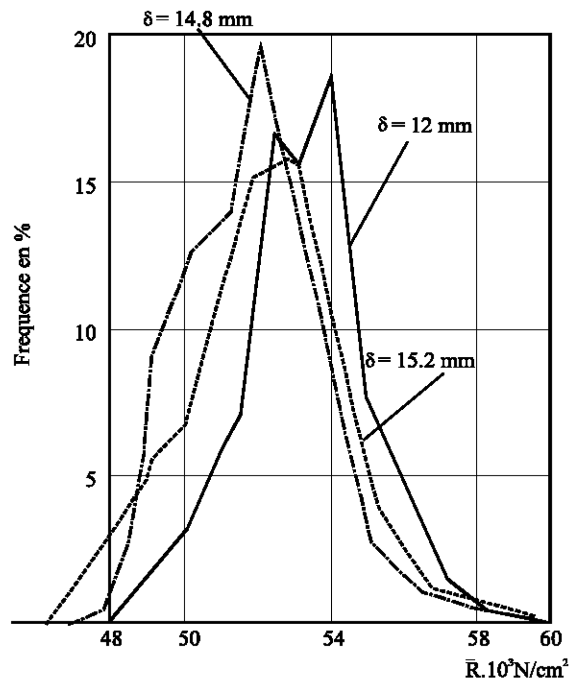

Fig. 6: Strength limit distribution curve for specimens of different thickness

Table 1:

Average values (Mathe- -matical expectation of calculation quantities)	Quadratique deviation of the calculation quantities	Variance coefficients of calculation quantities
$\bar{R}_t$ = 5, 259. 10^4 N/cm^2	σ_R = 0, 0258. 10^4 N/cm^2	V^R = 0, 0495
$\bar{\delta}_t$ = 11, 89 mm	σ_δ = 0, 2135 mm	V_δ = 0, 01795
$\bar{D}$ = 1196 mm	σ_{Din} 2, 343 mm	V_{din} = 0, 00196

average length and whose tube metal strength characteristics, determined by tests on specimens were $\bar{R}_t = 5{,}259.10^4\ \text{N/cm}^2$, $\bar{R}_{0,2} = 4{,}411.10^4\ \text{N/cm}^2$. These tubes are subjected to an internal pressure p = 7, 5 Mpa. The results of the statistical treatment of the data obtained for mechanical tests on X52 steel specimens are recorded in Table 1.

The welded joints in tubes constitute the weak link of a conduit. To argument this, the dependence of the safety characteristic γ and the tube rupture probability P_r has been studied in terms of the reserve coefficient ç for a tube supposedly without weld Fig. 7. If the reliability of a tube supposed without weld joints of dimensions 1220×12 mm made of X52 steel is calculated for $C_{eq} = 0,65\bar{R}_t$, then the reserve coefficient is found to be equal to 1,55, the safety characteristic γ = 9,77 and the rupture probability P_r = $1,93.10^{-8}$. This corresponds to a reliability of the conduit P(T) = 0,99999999. It results that the weld joints reliability determines almost completely the reliability level of a conduit, this confirms the validity of the approach used in this communication.

The results of the study of the influence of the weld joints on the reliability are shown in Fig. 8. It is noted from the graph that:

- P(T) = 0,99 corresponds to γ_{ad} = 4, 5 and $\bar{\eta}_{0,2}(\gamma_{ad}) \geq 1,28$; while it is sufficient for P (T) = 0,90 to satsfy the condition $\bar{\eta}_{0,2}(\gamma_{ad}) \geq 1$.

Application: The sizing of four section of a conduit of 40 Km each is considered. The four sections are supposed from four different categories defined by the reliability required for each of the sections namely 0.95, 0.99, 0.999 and 0.9999. The calculation is made on the basis of the results from the statistical treatment of the mechanical tests on X52 steel specimens. The tubes with longitudinal welds of 1220 mm diameter and intended to work at a pressure of 75 Kgf/cm² and for a temperature variation of 40°C. The sizing in this case consists of determining the tube wall thickness by the approach proposed in this communication for each one of the four sections. To insure the strength of the tubes with a given non rupture probability, the stress C_N should go over $C_N^* = \bar{R} k_e k_h$ (expression 13). The calculation has shown that, practically for the tubes concerned, the scale coefficient is 0.85. The homogeneity coefficient k_h is determined taking into account expressions (14), (15) and (16).

For a test pressure of a tubes of 97.5 Kgf/cm², the necessary tube wall thickness of the sections under consideration is determined taking into account expressions (20) to (24). The thickness values calculated for each section are respectively 1.37 cm for P(T) = 0.95; 1.48 cm for P(T) = 0.99; 1.54 cm for P(T) = 0.999 and 1.60 cm for P(T) = 0.9999. It is required to prealably determine the minimum rupture probability of a tube corresponding

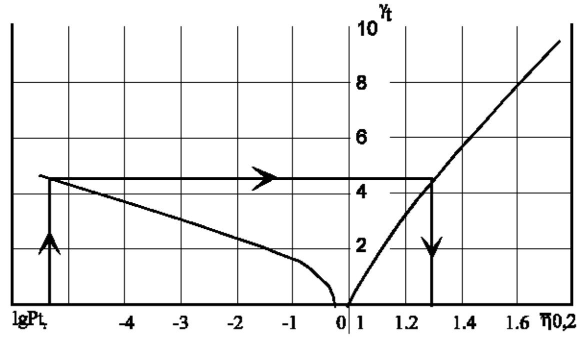

Fig. 7: The dependence of the safety characteristics γ and the rupture probability P_r^t in terms of the reserve coefficient for a tube. Supposedly without weld joints

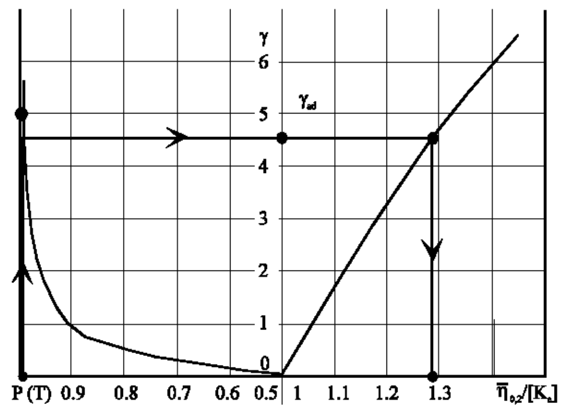

Fig. 8: Dependence of reliability function P(T) and the safety Characteristic γ on the reserve coefficient η_r for a tube with Longitudinal weld (i.e., α =0)

a given reliability of a section made of N tubes according to the expression: $P_r^t \leq 1 - \sqrt[n]{P(T)}$. For 40 Km section made of tubes of average length 12 m, n = 3.3×10^3 tubes.

CONCLUSION

The semi-probabilistic approach to the sizing of hydrocarbons transport conduits permits to avoid unjustified over sizing of tubes as a result of direct application of the recommendations of the norms enforced, while taking into account the reliability level required for the conduits. The tubes thicknesses determined by the approach considered are reduced by 20 % with respect to those determined by certain norms relative to pipelines projections. The advantage of the semi-probabilistic sizing procedures of conduits of hydrocarbons transport is that the user can modify them so that to respond to experience feedback on their calculated behaviour according to a past procedure. This permits to integrate the innovations to apply to pipeline projection calculations and to take account also of the new statistical data.

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