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Risk Analysis and Safety Evaluation for the Natural Gas Transmission Pipelines

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Abstract

This paper shows the particularities of developing a risk analysis in order to determine the safety distances between the national gas transmission pipelines system and the social and industrial objectives located in their neighborhood. Based on the event tree analysis on pipeline commissioning, on the causes and probability of occurrence of such events we chose to analyze the worst case scenario from the perspective of human health and safety, of the security of constructions, equipment and environment in the vicinity of the pipeline and, taking this worst case scenario into account, we drafted a procedure for the determination of the safety distances. The paper also shows the main physical and procedural means and methods to remedy and settle the risk entailed by the operation of the gas transmission pipelines for the purpose of providing some rationally sized safety areas.

Key words: *natural gas transmission pipeline, risc analysis, safety assessment, risc transect diagram*

Introduction

The risk analysis for natural gas transmission pipeline – NGTP operation is based on the following assessments of hazards related to the gas transmitted: a) natural gas belongs to the category of highly inflammable substances (F +), b) natural gas can be considered a non-toxic substance, but potentially asphyxiating.

The main hazard that has to be considered when analyzing the risk associated with a NGTP corresponds to the following sequence of events: a) the NGTP fails, looses its tightness, and part of the gas transmitted is leaking; b) gas leaks are not detected and quickly stopped and there are large amounts of gas accumulations in the area where the leak occurred, exceeding the lower explosion limit; c) the gas accumulations area presents the conditions for the ignition or self-ignition of the mixture of air and natural gas leaking from the NGTP [1, 2, 5].

The causes leading to the NGTP failure can be separated into the following classes and categories: Class A – Defects generated by time-dependent factors: 1. defects caused by external corrosion; 2. defects caused by internal corrosion; 3. defects caused by stress corrosion cracking; Class B – Defects caused by stable factors: 1. manufacturing defects (of steel pipes, pipe welded joints, etc.) 2. construction defects (of pipeline welds, on site pipe bends, etc.);

3. defects of pipeline components (flanges, fittings, valves, etc.); Class C – Defects caused by factors independent of time: 1. defects caused by third party interference; 2. defects caused by incorrect operation of the NGTP; 3. defects caused by climate loads or ground movement (low temperature, bad weather, landslides, earthquakes, etc.) [2, 5, 9].

NGTP failures can be classified according to the size / area of rupture through which gas escapes A_{sg} or the hole diameter equivalent to the opening d_{oe}, as follows: a) small failures, usually $d_{oe} < 20$ mm, caused by local defects of the type "metal loss" (generated by corrosion or erosion), the crack-like defects (caused by accidental bending, due, for example, to landslides or earthquakes) or perforations by indentation (generated, for example, by third party intervention); b) moderate failures having 20 mm $\leq d_{oe} < D_e$, caused by the limited local pipe bursting in the axial direction; c) large failures by complete fracture of the pipe, where $d_{oe} \geq D_e$, generated by a combination of causes, such as large areas of pipe presenting local defects of the type "metal loss", NGTP overloading due to incorrect operation or to the action of accidental mechanical loads (landslides, earthquake, etc.), pipe or welded joints crack extension (due to pipe or welded joints lack of toughness or due to fatigue phenomena generated by NGTP operating pressure fluctuations, etc.) [5-9].

Principles for the Application of NGTP Risk Analysis

In order to perform the technical risk analysis for the operation of the NGTP belonging to the national gas transmission system – SNTGN, consisting of failure probability estimation and of assessing the consequences of NGTP failure, the authors have proposed the use of the event tree shown in Figure 1, the probability values specified in this figure being obtained by the statistical analysis of the SNTGN pipeline failure causes and consequences recorded over a period of 15 years [5]. By analyzing the information summarized in this figure it can be easily deduced that the worst event, having major consequences and occurring during the NGTP operation is failure caused by explosion with / followed by fire, which can have destructive effects due to: a) heat generation; b) generation of shock waves (overpressure); c) generation and expulsion of solid fragments (from steel pipes and the anticorrosion coating of the failed NGTP, from the soil where the failed NGTP section had been buried, etc.); usually to achieve conservative results, risk analysis considers only the effect of heat generation (the thermal effect) of such event, and, of course, correlated with the hazard probability of the event [1, 5].

Various models can be used to assess the thermal effect of an explosion with fire, the simplest being the model of the punctual (single) thermal radiation source, the calculation of which being presented in Figure 2. This model is based on the followings [2-6]:

a) exposure heat intensity q_{ps} corresponding to a site situated at a distance r from the source of thermal radiation generated by the explosion, can be calculated with the formula:

$$q_{ps}(r) = \frac{\eta_{zi} m_p h_c}{4\pi r^2} \tau_a, \tag{1}$$

where m_p is the fuel mixture mass flow rate in kg/s, h_c is the specific combustion enthalpy (for methane and natural gas, which is predominantly methane, $h_c \cong 50$ MJ / kg), τ_a is the atmospheric transmission coefficient in the area where the explosion occurred, (it may be considered conservatively $\tau_a = 1$), and η_{zi} is proportion of radiation emitted in relation to the total heat of combustion released ($\eta_{zi} = 0.2$).

b) fuel mixture mass flow rate m_p can be determined by applying the formula:

$$m_p = A_{sg} \mu_{sg} \psi_g \sqrt{2 p \rho_g}, \tag{2}$$

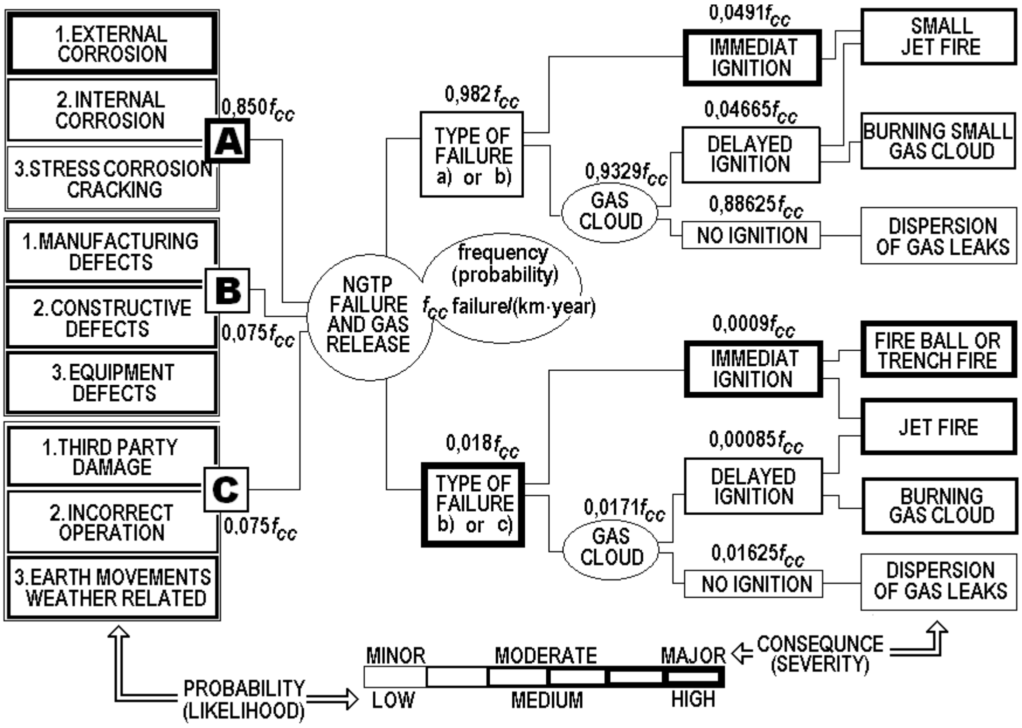

Fig. 1. Structure of event tree in NGTP risk assessment

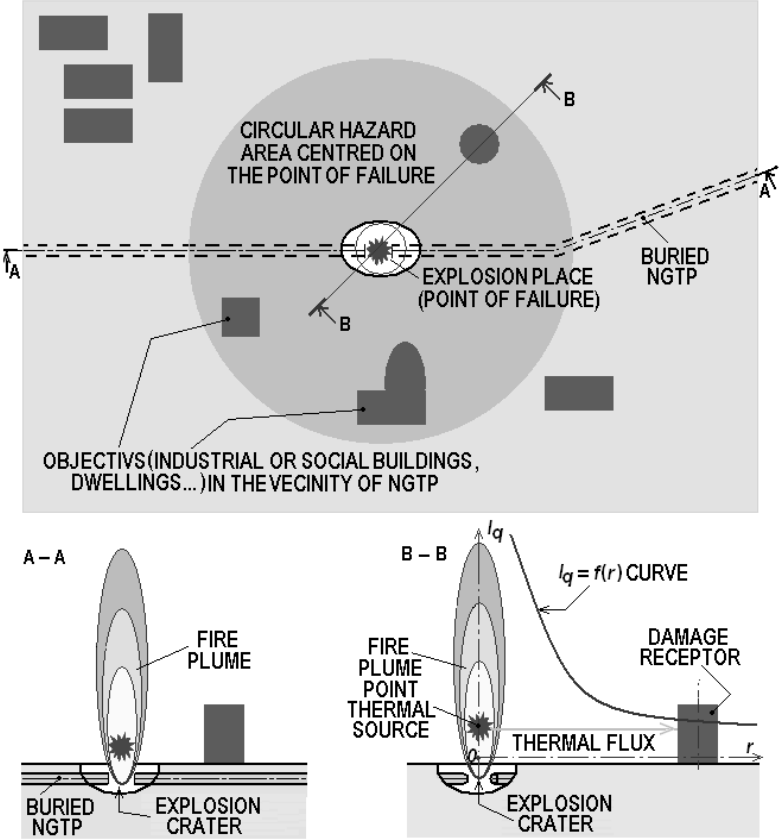

Fig. 2. Scheme of the zone subject to the thermal effects caused by the explosion and fire of a NGTP

where A_{sg} is the area of the opening (hole) through which gas leaks, μ_{sg} is a coefficient describing the conditions for gas leaking through the hole as a consequence of the NGTP failure (it describes the so-called outflow rate and it may be considered $\mu_{sg} = 0.59$), p is the NGTP operating (gauge) pressure ρ_g, being the average density of the gas transmitted through the NGTP (at the operating pressure p and temperature T_o), and ψ_g, being a complex factor, characterizing NGTP transmitted gas behaviour at decompression, are defined through the following formulas:

$$\rho_g = \frac{p}{R_{gm} T_o}; \; \psi_g = \sqrt{\frac{\gamma_g}{\gamma_g - 1}\left[\left(\frac{p_b}{p}\right)^{\frac{2}{\gamma_g}} - \left(\frac{p_b}{p}\right)^{\frac{\gamma_g+1}{\gamma_g}}\right]}, \tag{3}$$

where R_{gm} is the specific gas constant (for methane and natural gas, which is predominantly methane, R_{gm} = 518.3 J/kg·K), p_a is the reference atmospheric (absolute) pressure (p_b = 100325 Pa), and γ_g is the isotropic exponent (the ratio between the NGTP transmitted gas specific heat values at constant pressure and volume).

The following formula is recommended for the calculation of the radius r_{ie} of the fire explosion impact zone for the purposes of risk analysis performed for the determination of safety distances:

$$r_{ie} = 0{,}3933 D_e \sqrt{\frac{p}{q_{psa}}}, \tag{4}$$

resulting r_{ie} in m, if D_e is in mm, p in MPa and q_{psa} in kW/m^2, relationship obtained by adapting equation (1) for the following risk assessment (conservative) scenario: a) NGTP failure by full bore pipe (guillotine) fracture (the leaking hole surface A_{sg} has a diameter $d_{oe} \geq D_e$); b) the leaking gas ignites within maximum 60 seconds following NGTP failure; c) it is known the acceptable level of the exposure heat intensity q_{psa} for the sites in the vicinity of the NGTP failure location.

The thermal effects of the explosions with fire depend on the duration of exposure τ_e, the weight of the exposure heat intensity q_{psa} and of the exposure duration τ_e of these effects being described by the thermal load / dose S_{to}, which may be defined as follows:

a) for the evaluation of the effects of thermal radiation on human health and life:

$$S_{to} = \tau_e q_{psa}^{4/3}; \tag{5}$$

S_{to} determined by (5), with q_{psa} in kW/m^2 and τ_e in s, is considered expressed in thermal dose units, written as tdu;

b) for the evaluation of the effects of thermal radiation on residential buildings and various sites located in the vicinity of the NGTP:

$$S_{tl} = \tau_e^n (q_{psa} - q_{li}), \tag{6}$$

where q_{li} is the limit of the exposure heat intensity for which no ignition occurs (in kW/m^2), and n is an experimentally determined exponent.

The criteria recommended for risk analysis and based on the level of thermal load / dose have led to the correlations $q_{psa} = f(\tau_e)$ presented in Figure 3; the most used criterion for establishing safety distances is criterion “1 % fatality + τ_e = 30 s”, corresponding to a maximum level allowed for the intensity of exposure q_{psa} = 14.5 kW/m^2.

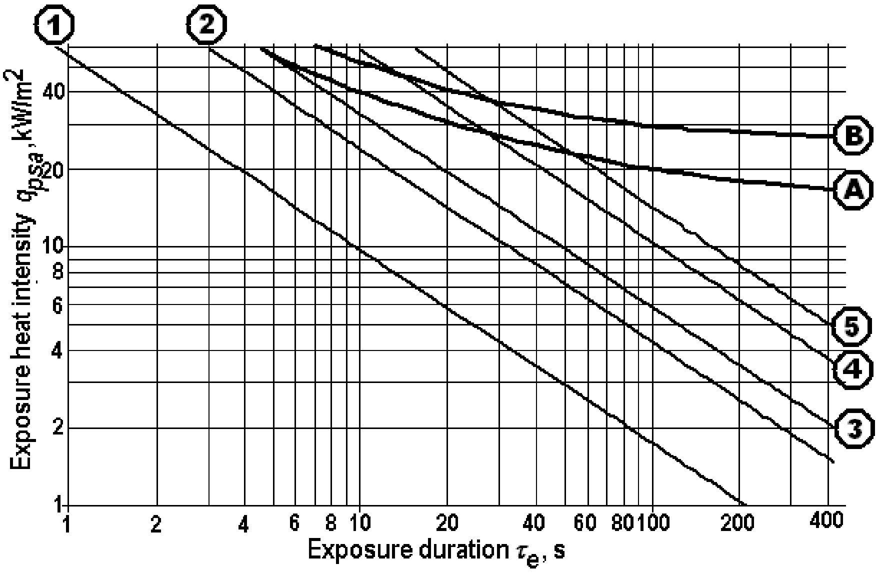

Fig. 3. Correlations between the intensity and the duration of exposure for various criteria:
1. Beginning of first – degree burns affecting the exposed population (S_{to} = 210 tdu);
2. Beginning of second – and third – degree burns affecting the exposed population (S_{to} = 700 tdu);
3. The 1 %fatality condition (S_{to} = 1060 tdu); 4. The 50 % fatality condition (S_{to} = 2300 tdu);
5. The 100 % fatality condition (S_{to} = 3500 tdu); A. Building and wooden object ignition if radiation is directed; B. Building and wooden object spontaneous ignition

Establishing Safety Distances for the Objectives in the Vicinity of the NGTP

Risk assessments for determining safety distances are usually based on individual risk transect $p_{ri} = f(y_{dc})$, the individual risk p_{ri} being defined by the probability that an accident occurring through the failure of a NGTP have lethal effects on humans situated in its vicinity, at a distance y_{dc}, measured in the direction normal to the longitudinal axis of the NGTP. The probability of occurrence and the effects of the technical hazards due to NGTP failure followed by fire on humans are usually considered when building the individual risk transect – IRT; the initial data necessary for the building of a NGTP IRT are as follows: a) NGTP constructive – functional characteristics: NGTP outer diameter D_e, wall thickness s_n and operating pressure p; b) the duration τ_e of population exposure to thermal radiation from a technical accident occurring through the failure of a NGTP followed by fire; c) the admissible thermal load / dose S_{toa} (calculated according to the criteria above); d) the dependency $p_{el} = g(S_{to})$ between the probability of lethal effects occurrence p_{el} and the level of the thermal load / dose S_{to}; based on the information summarized in Figure 3, we have obtained the following statistical regression relation for this dependency:

$$p_{el} = a_{el} + \frac{b_{el}}{1 + \exp[-(S_{to} - c_{el}) / d_{el}]}, \tag{7}$$

where: $a_{el} = -0.00321988$; $b_{el} = 1.020164955$; $c_{el} = 1948.543651$; $d_{el} = 265.0594549$, and the regression coefficient is $r_{pel} = 0.9995$; e) the failure frequency f_{cc} of the pipelines belonging to the system of which the NGTP is part and the weight p_{ci} of failures followed by fire of the pipelines of the system of which the NGTP is part; for the SNTGN pipelines $f_{cc} = 8 \cdot 10^{-3}$ failures/(km·year) and the p_{ci} values presented in Figure 1 may be considered (conservative).

The steps for the NGTP IRT building procedure are:

a) preparation of the calculation schemes for the individual risk p_{ri} of a (residential or working) site located at a distance y_{dc} from a NGTP, knowing the initial data (specified above); the calculation scheme is described in Figure 4;

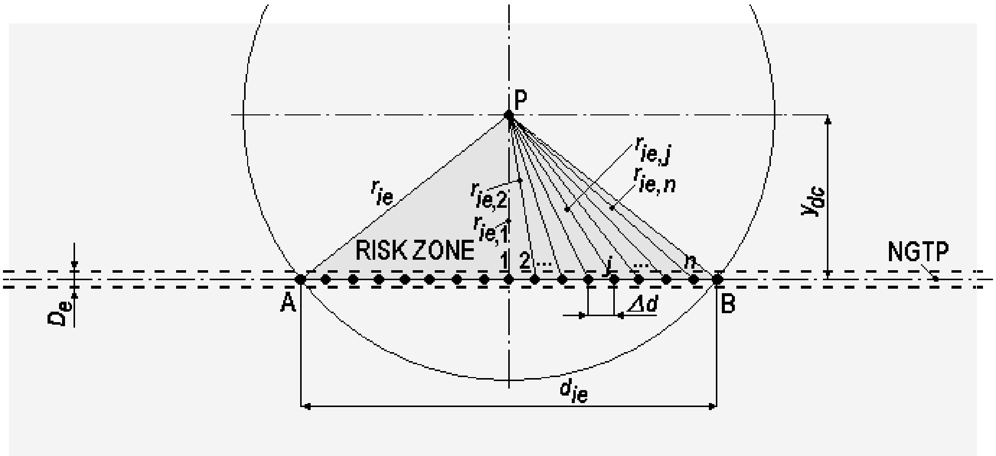

Fig. 4. Calculation scheme for NGTP individual risk

b) calculation of the impact radius values r_{ie} using the formula (4) and of the impact distance d_{ie} by the following formula:

$$d_{ie} = 2\sqrt{r_{ie}^2 - y_{dc}^2}\,; \tag{8}$$

NGTP failure in any location situated between point A and point B at a distance d_{ie} has dangerous effects on humans located in the point P site, such effects being dependent on the distance $r_{ie,j}$ between the place where the NGTP has failed and point P ($y_{dc} \le r_{ie,j} < r_{ie}$);

c) dividing the segment $\overline{AB}$ into $2n$ segments having the length $\Delta d = 0{,}5d_{ie}/n$ and the calculation of the impact radii values $r_{ie,j}$, $j = 1...n$:

$$r_{ei,j} = \sqrt{y_{dc}^2 + [(j-1)\Delta d]^2}\,; \tag{9}$$

d) calculation of the exposure heat intensity $q_{ps,j}$, where $j = 1...n$, for each radius $r_{ei,j}$:

$$q_{ps,j} = 0{,}15445p[D_e / r_{ei,j}]^2, \tag{10}$$

e) calculation of the thermal dose $S_{to,j}$, where $j = 1...n$, for each value $q_{ps,j}$, where $j = 1...n$ by applying the formula (5), and then, the determination of the lethal effects probability by using the equation (7) $p_{el,j}$, where $j = 1...n$;

f) calculation of the individual risk p_{ri} for the distance y_{dc} by the formula:

$$p_{ri} = 2p_{ci}f_{cc}\Delta d\sum_{j=1}^{n} p_{el,j}\,, \tag{11}$$

p_{ri} being the annual number of cases in which the technical hazards could cause lethal effects on humans situated at a distance y_{dc} compared to the NGTP analyzed.

By applying the above procedure for different distances $y_{dc} \in (0;r_{ie}]$, the dependency $p_{ri} = f(y_{dc})$, representing the IRT for the NGTP analyzed, can be represented graphically. The influence of the factors D_e, p and S_{toa} on the NGTP IRT is described in Figure 5; of course, as indicated by formula (11), the IRT is also influenced directly by p_{ci} and f_{cc} values that describe implicitly the attention given to the NGTP monitoring, inspection and maintenance over its normal operation life N_{nu} .

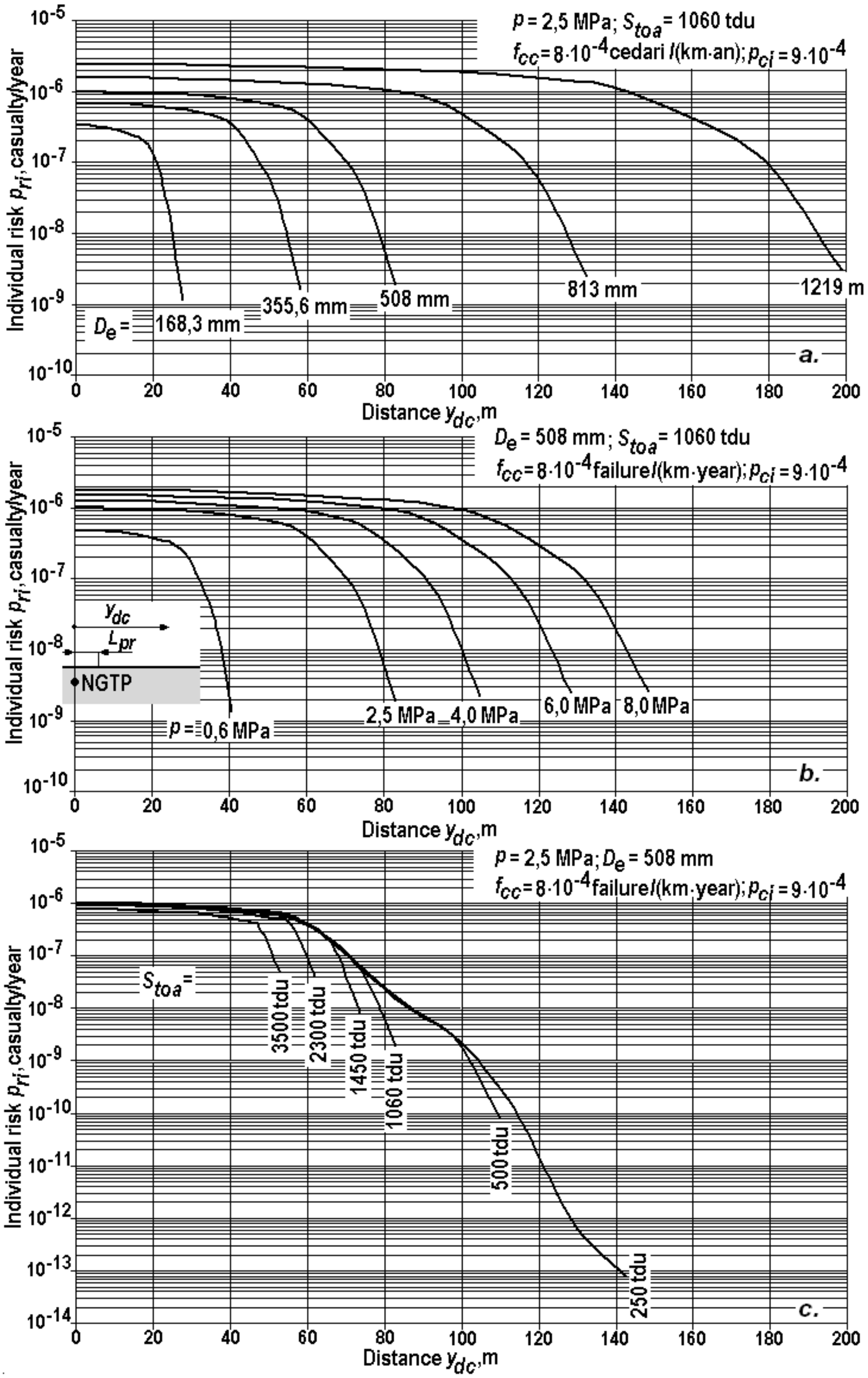

Fig. 5. The influence of various factors on the NGTP IRT:
a. the influence of the NGTP outer diameter; b. the influence of the NGTP operating pressure;
c. the influence of the admissible thermal load / dose

The criterion that should be applied for the interpretation of the results obtained by building the IRT for the NGTP are as follows: *the NGTP individual risk is acceptable if, for all* y_{dc} *distances corresponding to sites involving the population presence in the vicinity of the NGTP, the value* p_{ri} *of the individual risk is below the maximum acceptable level* p_{rad} ($p_{ri} < p_{rad}$); usually $p_{rad} = 10^{-5}$ is considered, and $p_{rad} = 10^{-6}$ can be used for the areas on the NGTP route in the vicinity of which there are high population density sites. The safety distance L_{sc} is the shortest distance y_{dc} (from a site involving the presence of humans to a NGTP) for which the condition $p_{ri} < p_{rad}$ is fulfilled [5-9].

If when designing a NGTP it is found that it is not possible to adjust the route as to ensure that a site in its vicinity is located at a distance $y_{dc} > L_{sc}$, p_{ri} risk mitigation measures must be taken. The methods by which the NGTP risk can be maintained within the acceptable range or mitigated can be classified into two categories [5, 7-9]:

a) physical methods, which include the following methods (and similar): a.1. the NGTP convenient sizing method referring to the selection of the convenient NGTP pipe steel resistance and / or rational adoption of the wall thickness for these pipes; a.2. the method of the convenient selection of the NGTP anticorrosive coating type and size; a.3. the method of the convenient selection of the NGTP laying depth; a.4.the method of application of NGTP protection elements (reinforced concrete slabs, polyethylene or steel plates, etc.) or of the NGTP laying into concrete channels; a.5. the method of using crack arrestors (elements located on the NGTP in vulnerable areas to enhance the mechanical strength of the NGTP and to ensure a good capacity for the limitation of failure expansion).

b) procedural methods, including the following methods (and similar): b.1. the method of performing all the NGTP mounting and welding works with qualified procedures; b.2. the NGTP monitoring method for detecting gas leaks during operation; b.3. the method of the NGTP route visible marking to facilitate its monitoring and to prevent damages due to external interference (third party intervention); b.4. the method of the regular technical verification of the NGTP by intelligent pig in-line inspection, by pressure and gas leak tests or by direct examination (intervention pits).

The effects of the application of any NGTP risk mitigation method can be summarized through the multiplication factors F_{ir}, for the formula (11) frequency f_{cc} or weight p_{ci}, regarding individual risk p_{ri} calculation. Thus:

a) the multiplication factor F_{irF}, which takes into account the value of the design factor F considered when sizing the NGTP, can be calculated by the formula:

$$F_{irF} = \exp[0{,}97(F - 0{,}72)]; \tag{12}$$

b) the multiplication factor F_{irs} , which takes into account the NGTP pipe wall thickness s_n, can be calculated with the formula:

$$F_{irs} = \exp[-\alpha_F (s_n - 5)], \tag{13}$$

where s_n is in mm, and $\alpha_F = 0.24$, if the NGTP sizing considered $F = 0.72$; $\alpha_F = 0.31$, if the NGTP sizing considered $F = 0.50$; $\alpha_F = 0.39$, if the NGTP sizing considered $F = 0.30$;

c) the multiplication factor F_{irH} , which takes into account the NGTP underground laying, can be calculated by the formula:

$$F_{irH} = 0{,}33697 + 1{,}93023\exp(-H_p), \tag{14}$$

where the laying depth H_p is in m;

d) the multiplication factor $F_{ir\tau}$, which takes into account the interval of time at which the

NGTP monitoring and maintenance activities are programmed, can be calculated by the formula:

$$F_{ir\tau} = -0{,}06047 + 0{,}40020 \ln \tau_{si}, \qquad (15)$$

where the interval of time τ_{si} between the monitoring and maintenance activities is in days.

Each risk mitigation measure should be validated through the economic analysis of the value, in order to find out whether there is a convenient (rational) relationship between the expenses incurred by its application and the risk mitigating effects produced.

Conclusions

The issues analyzed and solved in this paper lead to the following conclusions:

a) NGTP risk analysis and safety assessment should use the event tree (fig. 1) proposed by the authors, the main hazard that should be considered, in terms of probability and consequences of occurrence, being the NGTP explosion with/followed by fire, the thermal (heat release) effect being the effect that should be assessed;

b) Risk assessments aiming at the calculation of the safety distances between the national gas transmission pipelines and the social and industrial sites located in their vicinity should lead to the building of the IRT individual risk transect, by using the procedure described in the paper and by considering all the factors (presented in the paper) that may influence its configuration;

c) The criteria that should be applied for the interpretation of the results obtained by the building of the NGTP IRT is the following: *the NGTP individual risk is acceptable if, for all the distances to the sites involving the population presence in the vicinity of the NGTP, the value of the individual risk* p_{ri} *is below a maximum acceptable level* p_{rad};

d) Physical and procedural methods should be applied in order to ensure rational values of the safety distances.

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Analiza riscului şi evaluarea siguranței pentru conductele de transport al gazelor naturale

Rezumat

În lucrare se prezintă particularitatile realizarii analizelor de risc în vederea stabilirii distanțelor de siguranță dintre conductele apartinând sistemului national de transport al gazelor naturale şi obiectivele sociale şi industriale situate în vecinătatea acestora. Pe baza analizei arborelui de evenimente privind cedarea în exploatare a conductelor, a cauzelor şi probabilității de producere a unor astfel de evenimente, s-a selectat scenariul de cedare care poate avea consecințele cele mai grave pentru sănătatea şi viața oamenilor, pentru securitatea construcțiilor, echipamentelor şi mediului din vecinatatea conductelor şi, tinând seama de acest scenariu, s-a elaborat o procedură de determinare a distanțelor de siguranță. Sunt prezentate, de asemenea, principalele metode şi mijloace, de natur fizica si procedurala, de tratare si diminuare a riscului atasat functionarii conductelor destinate transportului gazelor naturale, în scopul prescrierii unor distanțe de siguranță de mărime rațională.