On the Issue of Calculating the Magnitude of the Potential Fire Risk of Emergencies on Gas Distribution Networks

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Abstract: An approach is proposed to determine the value of the conditional probability of human injury at a certain point of the territory as a result of the implementation of any scenario for the development of fire-hazardous situations on gas distribution networks associated with their rupture and subsequent gas ignition. Based on the analysis of the causes and factors determining the outcomes of accidents, taking into account the peculiarities of technological processes of natural gas transportation, typical accident scenarios are identified. For each scenario, the values of the probability of occurrence of emergency situations are calculated. A method for determining the probability of finding people in the residential area of gas pipelines is proposed.

1. Introduction

Access to energy resources for people and business is an important aspect of the economic development of the regions of the Russian Federation. This includes the ability to connect industrial facilities, social facilities, apartment buildings, as well as private households to gas supply networks.

Central gas supply has two very important advantages. Firstly, it is a low price. It's no secret that natural gas is one of the most economical fuels. Second, from an environmental point of view, natural gas is the cleanest type of fossil fuel. When burned, much less harmful substances are formed compared to other types of fuel.

The gas distribution network structure engineering (construction) is an important and essential element in the strategic development plan of the country. The Federal Special Purpose Programme includes the gasification of Russia's regions. This implies an increase in the volume of gas pipelines under construction.

However, in accordance with fire safety requirements, fire hazard analysis shall precede the start of basic design. Design solutions for a gas distribution networks construction shall be developed based on the fire hazard analysis results.

And here a problem arises: there is a lot of methodological material on determining the numerical value of the immediate factors of gas pipeline emergencies (blast wave, thermal radiation intensity) at a certain distance from the location of the emergency situation [1]. As for the evaluation of these human impacts, the mechanism for determining the numerical values of the impacts is not entirely clear. The main regulatory document used to assess fire hazards is the "Methodology for Determining Estimated Values of Fire Hazards at Industrial Sites" [9].
Regulatory documents [1] determine the potential risk estimated value, which is one ten millionth per year. If this value is exceeded, the basic design should determine additional measures to protect the designing object and people in the area around it [10].

It follows from this document that the value of the potential fire risk $P(a)$ (year$^{-1}$) (hereinafter referred to as potential risk) at the particular point $(a)$ both in the Site and in the residential area near the Site is determined by the formula [9, 16-17, 20]:

$$P(a) = \sum_{j=1}^{J} Q_{dj}(a) \cdot Q_{j},$$

where $J$ is the number of fire scenarios (fires, logical event tree branches);

$Q_{dj}(a)$ is a conditional chance of affecting a person at a certain point in the area $(a)$ as a result of the $j$-th scenario of fire hazards corresponding to a certain accident initiating event;

$Q_{j}$ is an occurrence frequency of the $j$-th scenario of fire hazards during the year, year$^{-1}$.

While the $Q_{j}$ value determination is not a problem, the $Q_{dj}(a)$ value is non-transparent. And quite often designers use a method of adjusting the calculated potential risk values at the design site, so there is no burden on the client to take additional measures to improve the designing object safety. [2-8, 12, 14,18].

Thus, the article proposes an approach for determining conditional probability value for human injury in a certain territory point as a result of the implementation of any scenario of fire hazardous situations.

2. Determination of fire risks to human life and health

Designing gas distribution networks belong to the objects category of high risk of explosion and fire hazards [11, 15].

An explosive mixture cannot accumulate in an open space; in the event of a gas line rupture, the natural gas will ignite with the formation of a "flare stack".

The main causes of accidents on gas pipelines can be:

- mechanical damage to the pipeline as a result of improper excavation work in the pipeline's protected area;
- gas pipeline destruction due to periodic loading from vehicles and agricultural machinery passing over it;
- damage to the above-ground parts of the pipeline due to vehicles colliding with it;
- gas leakage due to corrosion damage to gas pipelines;
- damage to gas pipelines due to natural phenomena;
- damage of gas pipelines due to strength loss of welded joints;
- other causes.

Based on an analysis of the causes and determinants of accident outcomes, taking into account the characteristics of natural gas transmission processes and the properties and distribution of hazardous substances, the following typical accident scenarios can be identified on gas distribution networks [13,19].

Scenario Group $C_{1-7}$ – accidents on a gas pipeline with flow diameter up to 100 mm

Scenario group $C_{J+1}$ – accidents at the gas pipeline with complete rupture.

Input data to determine the probabilities of the scenarios above are:

1. Mass flow rate of gas through the formed hole;
2. The diameter of the damaged gas pipeline.

3. Determining the mass flow rate of gas

The mass flow rate of the compressed gas from the tank is determined by the formulas.

Based on the calculated mass flow rate values, the accident probability values are selected for each scenario. Their values are empirical and are taken from the reference literature [9, 19].
The next step is to build failure trees [9]. An example of such a tree is shown in Figure 1.

**Figure 1.** Scenario tree initiated by gas outflow from a 12.5 mm diameter orifice.

The frequency of each accident scenario is calculated by multiplying the frequency of the main event by the conditional probability of the final event, determined using the event tree. The calculation of the conditional probabilities of the calculated $C_i$ accident scenarios should be carried out using the following formulas [9]:

- for scenarios with gas combustion
  \[ P(C_i/ A) = P(B/A) \cdot P(C_i/ AB) \cdot P(C_i/ ABC), \quad i = 1, 2, \ldots \]
- for scenarios without gas combustion
  \[ P(C_i/ A) = P(B/A) \cdot P(C_i/ AB) \cdot P(C_i/ ABC), \quad i = 1, 2, \ldots \]

where: $A$ is an event which consists in the emergence of an accident (rupture of a gas pipeline); $B$ is an event of ignition of escaping gas immediately after the gas pipeline rupture; $B'$ is the event of no ignition of the expiring gas after the bursting of the pipeline; $C_i$ is an event consisting in the occurrence of at least one of the scenarios in group $C_i$; $C_{ij}$ is an event consisting in the implementation of the particular $j$-th scenario of the group $C_i$.

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The jetting of liquefied natural gas (LNG), vapour and liquid phase of liquified petroleum gas (LPG) and natural compressed gas creates a risk of diffusion flares.

A flare length $L_F$ (m) in jet combustion is determined by the formula [9]:

\[ L_F = K \cdot G^{0.4}, \tag{2} \]

where $G$ is the product flow rate, kg/s; $K$ is empirical coefficient, which is assumed to be 12.5 for compressed gas, 13.5 for LPG or LNG vapour phase, 15 for LPG or LNG liquid phase.

The flare length in case of jetting of combustible liquids is determined by the range (height) of the liquid jet.

The following assumptions are allowed in assessing the fire hazard of a burning flare in the jetting of compressed flammable gases, vapour and liquid phase of LPG and LNG:
the area of direct contact of the flame with the surrounding objects, i.e. the area of the most dangerous thermal impact, the intensity of which can be assumed 100 kW/m², is determined by the dimensions of the flare

- the flare length \( L_F \) is independent of the product flow direction and the wind speed;
- The greatest danger is posed by horizontal flares, the conditional probability of their realisation being 0.67;
- The human impact in the horizontal flare occurs at a radius equal to the length of the flare;
- the impact of the horizontal flare on the adjacent equipment, leading to its destruction (cascade development of the accident), occurs in the 30th sector, limited by a radius equal to \( L_F \);
- Outside the indicated sector at distances from \( L_F \) to 1.5 \( L_F \) the thermal radiation from the horizontal plume is 10 kW/m².

As for the air pressure wave parameters (overpressure \( \Delta P \) and compression phase momentum \( I^* \)), depending on the distance from the cloud centre, they are calculated based on the expected combustion mode of the cloud. Since in the event of an emergency, methane has a 4 class of fuel combustion \[9\], we have:

\[
R_X = R / (E / P_0)^{1/3}
\]  \hspace{1cm} (4)

where \( R \) is the distance from the centre of the cloud, m;
\( P_0 \) - atmospheric pressure, Pa;
\( E \) - effective energy reserve of the mixture, J.

The values of dimensionless pressure \( P_{X1} \) momentum of compression phase \( I_{X1} \) are calculated by the formulas \[9\]:

\[
P_{X1} = \left( \frac{u}{C_0} \right)^2 \left( \frac{\sigma - 1}{\sigma} \right) \left( 0.83 - 0.14 \frac{R_X}{R_0^2} \right);
\]  \hspace{1cm} (5)

\[
I_{X1} = W \cdot (1 - 0.4W) \left( 0.06 - 0.01 \frac{R_X}{R_0^2} - 0.0025 \frac{R_X}{R_0^3} \right);
\]  \hspace{1cm} (6)

\[
W = \frac{u}{C_0} \left( \frac{\sigma - 1}{\sigma} \right).
\]  \hspace{1cm} (7)

where \( \sigma \) is the expansion degree of the combustion products (for gas/air mixtures it is assumed to be 7, for dust/air mixtures 4);
\( u \) is the apparent velocity of the flame front, m/s.

The dimensional values of overpressure and momentum of the compression phase are determined by the formulas \[9\]:

\[
\Delta P = P_{X1} \cdot P_0;
\]  \hspace{1cm} (8)

\[
I^* = I_{X1} \cdot P_0^{2/3} \cdot E^{1/3} / C_0.
\]  \hspace{1cm} (9)

As a probabilistic criterion of defeat, the notion of a punch function is used. In the general case, the probit function \( P_r \) is described by the formula \[9\]:

\[
P_r = a + b \cdot \ln S,
\]  \hspace{1cm} (10)

where \( a, b \) are constants that depend on the degree of impact and the type of Object;
\( S \) - is the intensity of the applied factor.

All the necessary expressions are obtained to determine the probabilities \( Q_d(a) \) by the formula (1). In this case, it is necessary to transform these expressions, taking into account that only the probabilities of causing damage to people who are in the residential area of the design object are inv.
Suppose \( n \) persons are present on the site. The probability of damage \( j \)-th person is \( q_j, \ j = 1, n \).

Hypotheses \( \Gamma_1, \Gamma_2, \ldots, \Gamma_n \), should be offered as working hypotheses, each of which implies that the emergency system will result in damage to the people in the inhabited zone [22].

Then the probabilities of hypotheses \( P(\Gamma_i), i = 1, n \), are defined through the values of \( q_i, \ j = 1, n \) where \( q_i = 1 - q_j \) is the probability of \( j \)-th person being "unharmed".

The probabilities \( P(\Gamma_i), i = 1, n \) are the a priori probabilities of the hypotheses [22]. Experience consists in checking the fulfillment of the given conditions. The experiment consists in checking whether the given conditions are fulfilled. An expression for determining the probabilities of injury or death for personnel and people in a residential area can be represented as:

\[
P(\Gamma_i) = q_i \prod_{j \in [1, n]} (1 - q_j) = \frac{q_i}{P_i} \prod_{j=1}^{n} P_j,
\]

Thus obtained the dependence for determining the magnitude of the potential risk of death or injury to people in the residential area of the designing object.

### 4. Calculation results

To compare the existing and proposed approaches to determining the magnitude of the potential risk of accidents on the gas pipeline, the article presents the calculation results obtained by both methods.

Results based on the existing approach:

\[
P(E_i)_E = 3,06908 \cdot 10^8 + 1,2338 \cdot 10^{10} + 2,96887 \cdot 10^9 + 1,28703 \cdot 10^8 + 5,174 \cdot 10^{11} +
1,24501 \cdot 10^9 + 4,83735 \cdot 10^8 + 4,33555 \cdot 10^{10} + 3,19292 \cdot 10^9 + 2,04657 \cdot 10^8 + 1,83427 \cdot 10^{10}
+ 1,35085 \cdot 10^9 + 2,94168 \cdot 10^9 + 3,76992 \cdot 10^{10} + 8,81328 \cdot 10^{10} = 5,18 \cdot 10^8
\]

In the presented calculation, the value of \( Q \) is calculated using the probit function (10). The results are based on the proposed approach, in which the value of \( P(E_i) \) is determined by the formula (12):

\[
P(E_i)_P = 4,22 \cdot 10^7 + 1,2585 \cdot 10^{10} + 2,17887 \cdot 10^9 + 1,9878 \cdot 10^7 + 5,23 \cdot 10^8 +
1,4401 \cdot 10^9 + 4,735 \cdot 10^8 + 4,545 \cdot 10^9 + 3,22292 \cdot 10^9 + 1,1 \cdot 10^8 + 2,43 \cdot 10^8 + 1,87 \cdot 10^9 +
2,8 \cdot 10^9 + 3,1692 \cdot 10^9 + 4,5 \cdot 10^8 = 8,8951 \cdot 10^7
\]

As can be seen from the above calculations, the calculated value of \( P(E_i)_P \) obtained using the proposed approach is 17 times greater than the value of \( P(E_i)_E \) obtained by the existing approach - probit function. This makes it possible to more accurately determine the potential risk of injury and death as a result of accidents on gas distribution networks, as a result, increases the safety of gas distribution networks at the design stage, which, in accordance with [15], are hazardous production facilities.

As can be seen from the above calculations, the calculated value according to the proposed approach (14) is 17 times greater than the value determined using the probit function (13). This allows
us to judge that the method of determining the probability of finding people in a residential area, given in the article, allows us to more accurately determine the values of the potential risk of injury and death of people in the results of accidents on gas distribution networks and, as a consequence, to increase the safety of hazardous production facilities by design methods, which in accordance with [15] are gas distribution pipelines.

5. Conclusion
The approach proposed in the article makes it possible to reliably determine the probability of finding people in the residential area of the gas pipeline and calculate the value of the potential risk of injury in the event of emergencies on gas distribution networks.

If the calculated value of the potential risk of accidents on the gas pipeline exceeds the value established by the regulatory documents [1], the project should additionally provide for measures to improve the safety of gas distribution networks in accordance with the requirements of [21].

6. References
[1] Technical regulations on fire safety requirements: Federal Law of July 22, 2008 No. 123-FZ. Access from the legal system "Consultant Plus"
[2] Rules of the fire protection regime in the Russian Federation (approved by By the decree of the Government of the Russian Federation Of the Russian Federation dated April 25, 2012, No. 390) Access from inform. the legal portal "Garant"
[3] Rostekhnadzor order of December 15, 2020 N 528 On approval of federal norms and rules in the field of industrial safety "Rules for the safe conduct of gas hazardous, hot and repair work"
[4] Gorshkova E E et al. 2016 Monitoring and forecasting of emergency situations of natural and technogenic nature of economic objects Week of Science in SPbPU: materials of the Scientific Conference with the international (St. Petersburg: St. Petersburg State Polytechnic University. Peter the Great University. Institute of military-technical education and security) pp 11-14
[5] Gorshkova E E, Krutilov A S 2015 Engineering measures ... Safety in emergency situations: SB. nauch. works vseros. nauch.-pract. Conf. SPb.: S.-Peterb. Polytechnic University of Peter the Great pp 239-245
[6] Prisyazhnyuk N L, Shishkov Yu A 2018 Fire risk assessment of the territory of the Krasnoyarsk Territory Historical experience, current problems and prospects of educational and scientific activities in the field of fire safety: collection of abstracts of the proceedings of the international nauch.-pract. Conf: M.: gallery: handover of cars of EMERCOM of Russia
[7] Anyhow V I, Ostudin N I, Soroka A V 2016 Methods of analysis of the information needs of the officials of the centers for crisis management of the Russian emergencies Ministry Natural and technological risks (physical-mathematical and applied aspects) 4(20) pp 18-28
[8] Antyukhov V I 2009 System analysis and decision-making edited by V S Artamonov S(t. Petersburg: St. Petersburg State University of the Ministry of Emergency Situations of Russia) 398
[9] Order of the Ministry of Emergency Situations of the Russian Federation of July 10, 2009 N 404 "On approval of the methodology for determining the calculated values of fire risk at production facilities" (with amendments and additions of 14.12.2010 N 64)
[10] Resolution of the Government of the Russian Federation of 31.03.2009 N 272 "On the procedure for conducting calculations for assessing fire risk"
[11] Zimonin A A, Firsov A V, Butenko V M 2014 Traumatization of people in fires Technosphere security technologies 5(57) pp 6-7
[12] Poroshin A A, Kharin V V, Bobrinev E V, Kondashov A A, Udavtsova E Yu 2019 Risks of death and injury of people in fires Bulletin of the National Railways 2 pp 127-132
[13] Fire statistics for 2007-2021 https://sites.google.com/site/statistikapozaro/home/rezultaty-raseteto/operativnye-dannye-popolzaram
[14] Kharin V V, Bobrinev E V, Kondashov A A, Udavtsova E Yu 2019 A statistical approach to
assessing the degree of fire danger by the ratio of people injured and killed in fires. Bulletin of the National Research Center of the Belarusian Railways 4 pp 127-135

[15] Federal Law of July 21, 1997 N 116-FZ "On industrial safety of hazardous production facilities"

[16] Shvyrkov S A and others 2012 Fire safety of technological processes: textbook under total. ed. S A Shvyrkova (M.: Academy of State Fire Service of the Ministry of Emergency Situations of Russia) 388

[17] Brushlinsky N N et al 2016 Fire risks: textbook. allowance (M.: Academy of EMERCOM of Russia) 66

[18] Yakush S E, Esmansky R K 2009 Analysis of fire risks. Part I: Approaches and methods Problems of risk analysis Vol 6 3 8-27

[19] Rostekhnadzor Order of December 26, 2018 N 647 On approval of the Safety Guide "Methodology for assessing the risk of accidents on threats to a gas pipeline facility"

[20] Tuchkova O A, Stroganov I V, Khairullin R Z 2019 Fire risk assessment: teaching aid Ministry of Education and Science of Russia, Kazan. nat. issled. technol. un-t. (Kazan: KNRTU Publishing House) 124

[21] SP 42-101-2003 General provisions for design and construction of gas distribution systems from metal and polyethylene pipes

[22] 2006 Probability theory: Textbook, for universities E S Wentzel 10th ed., Ster. (M.: Higher school) 575