Safety assessment of gas lines crossings under railways

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Abstract. The article provides an assessment of safety of train passengers when implementing accident scenarios related to depressurization of main gas line at a railway crossing. The analysis of the assessment results for the number of victims including those killed among train passengers obtained by the methodology in the industry regulatory documents has been made. This analysis of the assessment results for social risk of death of train passengers has revealed some sections of gas lines, which do not comply with the requirements of regulatory documents without additional safety measures. Some technical solutions have been proposed to reduce the risk of passenger death.

1. Introduction
According to the data by “Gazprom” Public Joint Stock Company [1] as of 2019, the total length of the gas transportation system in Russia was about 173 thousand kilometers.

At present, designing and construction activities of main gas lines are in progress as a part of international projects, as well as a part of programs of gas infrastructure development for Russian regions [2-4].

According to the website of the Federal Environmental, Industrial and Nuclear Supervision Service of Russia (Rostechnadzor) [5], accidents on gas main lines occur quite frequently. They are characterized by significant zones of impact of damaging factors, as well as significant material, environmental and social damage.

Table 1 shows the distribution of specific number of accidents due to their causes and diameters of gas lines of “Gazprom” Public Joint Stock Company [6].

2. Background
Ensuring safety of the personnel of the operating company, contractors, the public and third parties while operating main gas lines is priority.

3. Theoretical part
According to Clause 17 of the Regulation of Industrial Safety for Hazardous Facilities of Main Pipelines [7], when developing the design documentation for construction of main pipelines [8-13] their most hazardous sections shall be defined. These sections comprise their underground crossings under railways.

In accordance with the reference document [14], the increased risk of main gas lines crossing the roads and railways as compared with the linear part of main gas lines is a result of high probability of the following:
• ignition of gas escaped as a result of an accident / incident (ignition sources are cars and railway transport);
• mechanical damage to a gas line as a result of intensive economic activity along roads (excavation work);
• social and economic damage caused by deaths and injuries to people in motor and railway transport, especially, for high-traffic roads;
• physical damage to third parties (damage to road infrastructure, motor and railway transport);
• cascading development of accident when motor and railway transport carrying hazardous substances (such as chlorine, ammonia, etc.) is damaged.

Table 1. Distribution of specific number of accidents due to their causes and diameters of gas lines of “Gazprom” Public Joint Stock Company.

| Cause of accident | Outer diameter, mm | 219 | 273 | 325 | 530 | 720 | 820 | 1020 | 1220 | 1420 |
|-------------------|--------------------|-----|-----|-----|-----|-----|-----|------|------|------|
| Internal corrosion and erosion | 0.008 | 0.009 |     |     |     |     |     |      |      |      |
| Factory equipment defect | 0.007 | 0.021 |     |     |     |     |     |      |      |      |
| Defect in piping connection parts |     |      | 0.004 | 0.004 |     |     |     |      |      |      |
| Pipe defect |     |      | 0.021 | 0.017 | 0.026 | 0.075 | 0.035 | 0.046 | 0.010 |      |
| Diversion |     |      | 0.007 | 0.027 | 0.010 |     |     | 0.006 | 0.046 | 0.004 |
| External corrosion, if stress-corrosion cracking is excluded | 0.021 | 0.017 | 0.035 | 0.050 | 0.035 | 0.012 | |      |      |      |
| Violation of operating conditions and modes |     |      |     |     |     |     | 0.009 | 0.006 |      |      |
| Damage during operation |      |      |      | 0.081 | 0.054 | 0.041 | 0.034 | 0.026 | 0.075 | 0.023 | 0.008 | 0.002 |
| Other causes |     |      |      |     |     |     |     | 0.009 |      |      |      |
| Natural disaster | 0.066 | 0.010 | 0.051 | 0.009 |     |     |     | 0.004 | 0.004 |      |
| Stress corrosion |     |      | 0.008 | 0.035 |     |     | 0.076 | 0.189 | 0.098 |      |
| Construction defects | 0.015 | 0.081 | 0.010 | 0.017 | 0.044 | 0.100 | 0.059 | 0.089 | 0.025 |      |
| Fatigue damage |     |      |     |     |     |     | 0.010 |      |      |      |
| Total | 0.176 | 0.162 | 0.144 | 0.152 | 0.201 | 0.299 | 0.240 | 0.401 | 0.150 |      |

According to paragraph 5.5.3.1 of the Risk Assessment Procedure for Accidents at Hazardous Industrial Facilities of Main Gas Lines [15], one of the steps in the quantitative risk analysis is to determine the anticipated number of casualties and injuries among the public including train passengers at railway crossings in the potential damage area affected by the prevailing adverse factor.

There are no procedures to estimate the number of casualties and injuries among train passengers at underground railway crossings approved by the fire and / or industrial safety executive authorities (such as the Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters, and Rostechnadzor).

In paragraph 5.5.4.11 of the Risk Assessment Procedure for Accidents at Hazardous Industrial Facilities of Main Gas Lines [15] there are formulas for determining economic damage: number of damaged and destroyed cars of a moving train in case of an accident at the underground railway crossing of main gas line when exposed to a given adverse factor.

The procedure to estimate the number of casualties and injuries among passengers of trains at underground railway crossings is given in the industry standard – Guidelines for Risk Analysis of Hazardous Industrial Plants of “Gazprom” Joint Stock Company Gas Transport Facilities [16].
According to paragraph 5.9.9.6 of the Guidelines for Risk Analysis of Hazardous Industrial Plants of “Gazprom” Joint Stock Company Gas Transport Facilities [16], the number of injuries among passengers for an accident at a main gas line crossing under railways shall be calculated by assuming the following:

- gas line rupture occurs at the point of the main gas line (outside the pipe sleeve (casing)) nearest to the railway track;
- at the moment of accident, the middle of the train crossing the underground gas line is above the axis of the gas line;
- the train cars provide partial protection for the people inside against the exposure to the adverse factor (vulnerability factor $\nu = 0.5$).

When calculating the size of the potential damage area it is recommended to assume the following speed of trains:
- for electric and long-distance passenger trains it is 70 km/h;
- for fast trains – 90 km/hour;
- for high-speed express train – 170 km/hour.

The total number of victims in an accident at a railway crossing is calculated using the following formula (1):

$$N_{\text{victims}} = \nu \left( \frac{L_1}{L_{\text{car}}} \right) N_{\text{car}}$$

where $L_1$ is the length of the railway section within the potential damage area (1%), m; $L_{\text{car}}$ is the length of one train car, m ($L_{\text{car}} = 25$ m); $N_{\text{car}}$ is number of persons per car ($N_{\text{car}} = 54$ persons for a long-distance couchette car; $N_{\text{car}} = 132$ persons for a suburban electric train).

The number of dead passengers is calculated by the formula (2):

$$N_{\text{casualties}} = 0.5 \nu \left( \frac{N_{\text{car}}}{L_1} \right) \left( \frac{L_{100}}{L_1} + L_1 \right)$$

where $L_{100}$ is the length of the railway section within the absolute (100%) damage area, m.

The number of injured passengers is calculated by the formula (3):

$$N_{\text{injured}} = N_{\text{victims}} \cdot N_{\text{casualties}}$$

Let us evaluate the correctness of calculations made using the proposed formulae.

4. Case studies

According to Table 5-2 of the Risk Assessment Procedure for Accidents at Hazardous Industrial Facilities of Main Gas Lines [15] and paragraph 5.5 of the Guidelines for Risk Analysis of Hazardous Industrial Plants of “Gazprom” Joint Stock Company Gas Transport Facilities [16], the main calculation scenarios for accidents on a main gas line are: “Trench Type Fire” (“Column of Fire”) – MG1, and “Jet Flames” – MG2.

Let us consider the destruction of a main gas line section with diameter of 1020 mm, wall thickness of 16 mm, maximum operating pressure $P_{\text{max}} = 9.8$ MPa.

The calculation of geometrical flame parameters for the scenarios “Trench Type Fire” (MG1), “Jet Flames” (MG2) has been done according to Appendix 10 of the Risk Assessment Procedure for Accidents at Hazardous Industrial Facilities of Main Gas Lines [15], as well as paragraphs E.4.1, E.4.2 of Appendix E of the Guidelines for Risk Analysis of Hazardous Industrial Plants of “Gazprom” Joint Stock Company Gas Transport Facilities [16] for the case of critical gas escape ($Q_{\text{cr}} = 10691$ kg/s).

The results of calculation of geometric flame parameters for the scenarios “Trench Type Fire” (MG1), and “Jet Flames” (MG2) are summarized in Table 2.
Table 2. Results of calculation of geometrical flame parameters for the scenarios “Trench Type Fire” (MG1), “Jet Flames” (MG2).

| Scenario of accident         | Length of torch (jet), m | Torch (jet) diameter, m |
|------------------------------|--------------------------|-------------------------|
|                              |                          | small | big         |
| “Trench Type Fire” (MG1)     | 472                      | 236   |             |
| “Jet Flames” (MG2)           | 709                      | 1.32  | 184         |

The “Gas Jet Burning” module of the “TOXI+Risk” program complex has been used to determine the thermal radiation intensity for the above scenarios.

Results of thermal radiation impact area calculation (the half-width is perpendicular to the jet axis) for the scenarios “Trench Type Fire” (MG1) and “Jet Flames” (MG2) are given in Table 3.

Table 3. Results of thermal radiation impact area calculation for the scenarios “Trench Type Fire” (MG1) and “Jet Flames” (MG2).

| Accident scenario       | Thermal radiation from torch (jet), m | Potential damage area, m |
|-------------------------|----------------------------------------|--------------------------|
|                         | 13.9 kW/m² | 10.5 kW/m² | 7.0 kW/m² | 4.2 kW/m² | 1% | 100% |
| “Trench Type Fire” (MG1)| 473        | 565        | 715       | 942       | 888 | 675  |
| “Jet Flames” (MG2)      | 385        | 451        | 561       | 727       | 715 | 572  |

The damage to people and material damage depending on the thermal radiation intensity are shown in Table B.2 [17].

Based on the obtained calculation results for potential damage areas, the total number of victims when implementing the scenario of “Trench Type Fire” (MG1) at the railway crossing will be as per the formula (4):

\[
N_{\text{victims}} = 0.5 \left( \frac{2 \cdot 888}{25} \right) 54 = 1918
\] (4)

For the “Jet Flames” scenario, the total number of victims will be \( N_{\text{victims}} = 1544 \) people.

The number of casualties when implementing the scenario of “Trench Type Fire” (MG1) at the railway crossing will be as per the formula (5):

\[
N_{\text{casualties}} = 0.5v \left( \frac{N_{\text{car}}}{L_{\text{car}}} \right) (L_{100} + L_{1}) = 0.5 \cdot 0.5 \left( \frac{54}{25} \right) (2 \cdot 675 + 2 \cdot 888) = 1688
\] (5)

For the “Jet Flames” scenario, the number of casualties will be \( N_{\text{casualties}} = 1390 \) persons.

However, taking into account the number of cars in a passenger train (15 units) recommended by paragraph 5.5.4.11 of the Risk Assessment Procedure for Accidents at Hazardous Industrial Facilities of Main Gas Lines [15], it should be noted that the estimated number of casualties significantly exceeds the total actual number of passengers on a train, which is about 810 persons.

Thus, the results of calculations of number of victims on a train obtained using the procedure presented for Guidelines for Risk Analysis of Hazardous Industrial Plants of “Gazprom” Joint Stock Company Gas Transport Facilities [16] are incorrect and give overestimated values.

According to paragraph 3.1 of the Risk Assessment Procedure for Accidents at Hazardous Industrial Facilities of Main Gas Lines [15], as well as Clause 34 of the Methodology Basis for Hazard Analysis and Accident Risk Assessment for Hazardous Industrial Facilities [18], it is recommended to determine social risk factors among other quantitative risk factors.
According to the condition specified in Clause 43 of the Procedure for Determination of Design Values for Fire Risk for Industrial Facilities [19], it is recommended to determine social risk for scenarios with 10 casualties and more.

According to Clause 44 of the Methodology Basis for Hazard Analysis and Accident Risk Assessment for Hazardous Industrial Facilities [18], social risk is determined by a sum of accident scenario implementation frequency and the anticipated number of casualties.

Thus, for the number of casualties $N_{\text{casualties}} = 1688$ persons (scenario MG1 “Trench Type Fire”) the social risk will be as per the formula (6):

$$ R_{soc} = 1.4 \times 10^{-7} \times 0.24 \times 888 = 3.0 \times 10^{-5} $$

where $1.4 \times 10^{-7}$ per 1 m of pipeline per year is the average statistical frequency of main gas line depressurization (Procedure for Determination of Design Values for Fire Risk for Industrial Facilities [19]);

0.24 is conditional probability of MG1 “Trench Type Fire” scenario (Table 5.7 of the Risk Assessment Procedure for Accidents at Hazardous Industrial Facilities of Main Gas Lines [15], Table 5.7 Guidelines for Risk Analysis of Hazardous Industrial Plants of “Gazprom” Joint Stock Company Gas Transport Facilities [16]);

888 m is the length of gas line section equal to the size of potential damage area (1%), where the scenario of “Trench Type Fire” (MG1) with the given number of casualties is probable.

For the number of casualties $N_{\text{casualties}} = 1390$ persons (“Jet Flames” (MG2) scenario) the social risk will be $R_{soc} = 7.2 \times 10^{-5}$ per year.

However, in accordance with the requirements of Clause 93, Federal Law Technical Regulations on Fire Safety Requirements [20], and taking into account the specifics of the functioning of gas transport processes, the value of social risk of death of train passengers shall not exceed $R_{soc} = 10^{-5}$ per year.

5. Conclusion

It is necessary to apply an additional set of regulatory, engineering and organizational solutions to protect train passengers at points of main gas line crossings under railways.

Earlier some engineering solutions have been proposed [14]: increase in the length of protective sleeves (casings); increase in the length of junction areas above the normative value.

The increase in the length of junction section above the normative value (outside the junction box up to 350-550 m depending on the diameter and operating pressure of main gas line) leads to a significant risk reduction (by an order of magnitude) on the railway bed. This effect is due to the improvement in main gas line construction quality within the required distances from the crossing and absence of any impact on the safety indices on the railway bed.

Further to the above, it is possible to use protective screens to reduce the thermal impact of jet (torch) burning of gas on the train.

References

[1] Gazprom: Energy Company. https://www.gazprom.ru/about/production/transportation/ (accessed on May 25, 2020)

[2] Gazprom Mezhregiongaz. https://mrg.gazprom.ru/about/gasification/ (accessed on June 26, 2020)

[3] Resolution of the Russian Federation Government No. 903, 2016: About Order of Development and Implementation of Interregional and Regional Gasification Programs for Housing and Utility Services, Industrial and Other Companies. http://www.consultant.ru/document/cons_doc_LAW_204555/ (accessed on June 26, 2020)

[4] Federal Law No. 69, 1999: On Gas Supply in the Russian Federation. http://www.consultant.ru/document/cons_doc_LAW_22576/ (accessed on June 26, 2020)
[5] Federal Service for Environmental, Technological and Nuclear Supervision (Rostechnadzor). http://www.gosnadzor.ru/industrial/oil/lessons/, accessed on May 25, 2020

[6] Makhutov N A, Permyakov V N and Akhmetkhanov R S 2013 Risk Analysis and Protection of Critical Facilities of Oil, Gas and Chemical Industry (Tyumen: Tyumen State Oil and Gas University) p 560

[7] Closed Joint Stock Company “Scientific and Technical Center for Industrial Safety Research”, 2014: Safety Standards and Regulations for Hazardous Facilities of Main Pipelines, 20 (Moscow) p 40

[8] SP 36.13330.2012 2013 Federal Agency for Construction, Housing and Utility Services (Gosstroy), Main Pipelines (Moscow) p 92

[9] SP 86.13330.2014 Ministry of Construction, Housing and Utility Services of the Russian Federation (Minstroy) Main Pipelines (Moscow) p 175

[10] Russian Federation Government Resolution No.87, 2008: On Composition of Design Documentation Sections and Requirements for their Content. http://www.consultant.ru/document/cons_doc_LAW_75048/ (accessed on July 26, 2020)

[11] Federal Law No. 190, 2004 Russian Federation Urban Planning Code. http://www.consultant.ru/document/cons_doc_LAW_51040/; accessed on July 27, 2020

[12] Federal Law No. 384, 2009 Technical Regulations on Safety of Buildings and Structures. http://www.consultant.ru/document/cons_doc_LAW_95720/ (accessed on July 27, 2020)

[13] “Gazprom” Joint Stock Company 2006 Process Design Standards for Main Gas Lines: STO Gazprom 2-2.3-351-2009 Guidelines for Risk Analysis of Hazardous Industrial Plants of “Gazprom” Joint Stock Company Gas Transport Facilities (Moscow) p 377

[14] Kovalev S, Zhelezov K, Ershova A and Kirkin M 2017 Justification of Regulatory Requirements for Main Gas Line Crossings under Roads and Railways by Risk Analysis Methods Collection of Scientific and Technical Articles. Gas Science News 1(29) pp 143–154

[15] Closed Joint Stock Company “Scientific and Technical Center for Industrial Safety Research” 2019 Safety Manual Risk Assessment Procedure for Accidents at Hazardous Industrial Facilities of Main Gas Lines, 42 (Moscow) p 204

[16] STO Gazprom 2-2.3-351-2009 Guidelines for Risk Analysis of Hazardous Industrial Plants of “Gazprom” Joint Stock Company Gas Transport Facilities (Moscow) p 204

[17] GOST R 12.3.047-2012 Labor Safety Standards. Process Fire Safety. General Requirements. Methods of Control (Moscow: Standardinform) p 62

[18] Closed Joint Stock Company “Scientific and Technical Center for Industrial Safety Research” 2016 Safety Manual Methodology Basis for Hazard Analysis and Accident Risk Assessment for Hazardous Industrial Facilities 16 (Moscow) p 56

[19] Procedure for Determination of Design Values for Fire Risk for Industrial Facilities, 2009, 404. http://www.consultant.ru/document/cons_doc_LAW_91229/ (accessed on May 25, 2020)

[20] Federal Law No. 123, 2008 Technical Regulations on Fire Safety Requirements. http://www.consultant.ru/document/cons_doc_LAW_78699/ (accessed on May 24, 2020)