Scenario Analysis of the Risk of Gas Pipeline Failures in the North

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Abstract. Low temperatures and abnormal meteoconditions of the North have significant effect both on the accident frequency, and on accident development. Abnormal weather conditions of the North are characterized by the powerful temperature inversions arising at an anti-cyclone due to the emission of permafrost soil at extremely low temperatures of air and conditions of air stagnation. These abnormal conditions influence process of gas dispersion in the atmosphere, promoting its deceleration and formation of explosive concentration of gas at the Earth's surface. Based on the results of gas pipeline failures analysis occurred in the North, the main causes of gas pipeline accidents were identified, the gas leakage “fault tree” from the gas pipeline was developed with estimation of failures frequencies, and the frequency of emergency situations in case of gas leakage from the gas pipeline was estimated. The most dangerous scenarios of gas pipeline accident evolution have been identified and their risk levels in the zone of the damage factors have been assessed on the basis of acceptable risk criteria. It is justified to increase the action range of damage factors in an explosion of methane-air mixture cloud in open space at presence of temperature inversion.

1. Introduction

The gas pipeline is an important element of the gas supply system, as 70-80 % of all capital investments are spent on its construction. At the same time, of the total length of gas pipelines 70-80% are low pressure gas pipelines and only 20-30% - medium and high pressure gas pipelines. Low-pressure gas pipelines serve to supply gas to homes, public buildings and utility companies. Medium pressure gas pipelines supply low-pressure gas pipelines, as well as industrial and utility companies with gas through gas control stations. Gas is supplied through gas distribution plants to industrial plants and gas pipelines of medium pressure.

Most of the northern gas pipelines have an underground structural scheme of laying and are located in the zone of multi-frozen soils. Severe natural and climatic conditions of the North significantly reduce reliability and safety of gas pipelines operation. Uncontrolled development of emergency situations can lead to catastrophic destruction and loss of life.

Risk analysis is one of the essential components of safety and is carried out to identify individual sources of hazards and to assess their potential impact on possible damage that may be caused to the population, the environment and economic facilities.
2. Frequencies assessment of failures and scenarios of emergency situations development on gas pipelines of the North

The most important stage of risk analysis is assessment of frequency or probability of failures and scenarios of emergency development in gas pipelines.

Based on the results of gas pipeline failures analysis occurred in the North, the main causes of gas pipeline accidents were identified, the gas leak “fault tree” from the gas pipeline was developed with estimation of failures frequencies, figure 1.

The main causes of gas pipeline accidents are: possible mechanical effects of third parties — make up 22% of the possible causes of the accident, corrosion damages — 20%, welding errors — 24%, natural influences — 2%, damage accumulation, wear of material — 13%, ice blockages — 3%, depressurization of the flange — 16%.

Statistical analysis of the causes of gas pipeline accidents showed that the main causes of these events are organizational causes related to the human factor and technical reasons related to aging and wear of gas pipelines and corrosion damage.

The frequency of gas leakage from the gas pipeline is \(1.3 \times 10^{-3}\) km/year (figure 1), of which gas leakage at complete pipe rupture — \(1.74 \times 10^{-4}\) km/year. The most frequent failures are failures due to welding defects — \(3.09 \times 10^{-4}\) km/year, mechanical effects of third parties — \(2.9 \times 10^{-4}\) km/year, corrosion damages — \(2.51 \times 10^{-4}\) km/year and wear of material — \(1.74 \times 10^{-4}\) km/year.

The essence of the risk analysis consists in selection and processing of all available information for danger identification and an assessment of its possible consequences.

Generalization of accident probabilities according to various scenarios it is most convenient to carry out by logiko-probabilistic methods “fault trees” and “event trees” (FT/ET). Wide use of the FT/ET methods is caused by simplicity and clarity of the initial idea used at a problem setting of modeling.

Based on the results of analysis of known accidents of gas pipelines, which occurred at low temperatures, “event trees” of gas leakage from the gas pipeline has been developed [1] with estimation of emergency scenarios frequencies, figure 2.

Frequencies of scenario implementation are determined by the following formula:

\[
H(C_j) = F \cdot \prod_i P_{ji}
\]

where \(F\) — gas leakage frequency from gas pipeline, 1/(km · year),

\(P_{ji}\) — events probabilities of the scenario \(j, i = 1, 2, 3, \ldots\),

\(C_j\) — emergency scenarios, \(j = 1, 2, 3\ldots\)

3. Risk rating

Risk rating, along with identification, assessment and forecasting, is an integral part of the quantitative risk analysis of accidents. At the same time, rating as process safety management element in the technosphere.

The work [2] proposes the following levels of individual risk criteria for the population from existing hazardous production facilities: risk level more than \(10^{-4}\) per year — unacceptable risk zone; less than \(10^{-4}\) per year, but more than \(10^{-5}\) per year — strict risk control zone; less than \(10^{-5}\) per year — zone of acceptable risk.

By results of the analysis of ”event tree” of gas outflow from the gas pipeline, figure 2, the most dangerous events occur with a frequency about \(10^{-5}\) 1/(km · year). With the constant presence of a person in the zone of possible action of damaging factors, the individual risk will be about \(10^{-5}\) 1/(km · year) that corresponds to strict risk control zone.
Figure 1. “Fault tree” gas leakage from gas pipeline in North conditions.
Figure 2. "Event tree" of gas outflow from the gas pipeline at low ambient temperatures.

4. Effect of temperature inversion on the process of gas dissipation in the atmosphere and the magnitude of the shock wave during the explosion of the methane gas-air mixture cloud in the open area

Note that as a general principle, for large tables font sizes can be reduced to make the table fit on a page or fit to the width of the text.

Low temperatures and abnormal weather conditions of the North have a significant impact on the development of accidents. Abnormal meteorological conditions of the North are characterized by powerful temperature inversions arising in the anticyclone due to the radiation of permafrost soil at extremely low ambient temperatures, and air stagnation conditions. These abnormal conditions effect
the process of gas dispersion in the atmosphere, contributing to its slowing and the formation of explosive concentrations of gas at the Earth's surface. The resulting accumulation of explosive concentrations of gas at the Earth can further lead to explosion and fire. The area of exceptionally powerful and prolonged inversions is Yakutia. For the cold season, especially from December to February, most of the territory is characterized by weak winds and calms, which cause weak air mixing and therefore weak vertical heat exchange, so there are powerful ground inversions that increase in mountain areas.

The frequencies of formation of explosive methane gas-air mixture cloud in case of large volumes of gas leakage are shown in Table 1.

Table 1. The frequencies of cloud formation of explosive methane gas-air mixture in case of large gas leaks (scenario 5).

| Months   | The frequencies of cloud formation of explosive methane gas-air mixture, 1/(km∙year) |
|----------|----------------------------------------------------------------------------------------|
| November | 5.44 · 10^{-5}                                                                         |
| December | 5.8 · 10^{-5}                                                                           |
| January  | 5.56 · 10^{-5}                                                                          |
| February | 4.91 · 10^{-5}                                                                          |

Scenario 5 (figure 2) in a generalized view it is briefly described as follows: depressurization (rupture) of the pipeline with the outflow (emission) of natural gas in the environment → formation of methane gas-air mixture cloud → explosion (in the presence of an ignition source) → influence of the damage factors on recipients. To assess the parameters of the methane gas-air mixture cloud explosion, it is possible to recommend a safety guide as described in document [3]. But at long distances in the North, the influence of powerful temperature inversions on the parameters of a weak shock wave should be taken into account.

Table 2. Results of increase assessment in excessive pressure of $\Delta p_f$ (200 Pa) of a weak shock wave depending on the nature of temperature change with altitude at explosion of methane gas-air mixture cloud

| Temperature gradient with altitude | $\Delta p_{f0}$, kPa (before increase) | K | $\Delta p_{f_{inc}}$, kPa (after increase) | Degree of damage at $\Delta p_{f_{inc}}$ (after increase) | C | P |
|-----------------------------------|---------------------------------------|---|------------------------------------------|--------------------------------------------------------|---|---|
| inversion                         | 0.2                                   | 25 | 5                                       | light damage to buildings                                |   |   |
|                                   |                                       |    |                                         | possible shrapnel injuries                              |   |   |
| the raised inversion              | 0.2                                   | 100| 20                                      | average damage to buildings                              |   |   |
|                                   |                                       |    |                                         | serious tissue damage                                    |   |   |

where K - coefficient of possible increase in excessive pressure. $\Delta p_{f0}$ of a shock wave; C – constructions; P - personnel (population).
In work [5] experimentally obtained coefficients of possible increase of air shock wave depending on the nature of temperature change with altitude. With a negative temperature gradient, there is no increase in the overpressure of the shock wave. With a positive temperature gradient, it is possible to increase the overpressure of the shock wave from 5 to 100 times, depending on the nature of the inversion. Results of increase assessment in excessive pressure of $\Delta p_f$ (200 Pa) of a weak shock wave are presented in Table 2.

It can be seen from Table 2 that overpressure, having increased by 25 times in ground inversion and by 100 times in raised inversion, results in human injury at the same distance as was safe for humans in the absence of inversion. Thus, at long distances, the overpressure value increases in the presence of temperature inversion, resulting in an increase in the hazardous area.

5. References
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