Predictive assessment of man-made risks during oil-handling operations at tank farms

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Abstract. Predictive analysis of events associated with the depressurization of the tank during the filling of fuel showed the probability of the occurrence and development of fires resulting from the spread of clouds of flammable gases with concentrations corresponding to the concentration limits of ignition. It is shown that when fuel ignites with the development of a pool fire or when an air shock wave propagates as a result of an explosion of the fuel-air mixture, the damaging factors will have a negative effect, which will lead to destruction and damage to the operating personnel.

1. Introduction
A tank farm is a facility, where petroleum products are stored in storage tanks and oil-handling operations are carried out that can lead to fuel spills.

An emergency oil spill in amounts comparable to the volume of a railway tank or the volume of various reservoirs may result from emergency depressurization (full/partial destruction).

Causes related to equipment failure, the result of which can be depressurization of a tank or reservoir, include various hidden internal defects, such as corrosion, defective welds, metal fatigue phenomena and other causes considered in studies [1-2]. An emergency spill of petroleum products from reservoirs, subject to the presence of these hidden defects, may occur as a result of any internal or external influences (terrorist attacks, subversive actions). Reducing the risk of accidents provides for the safe operation of equipment [3-5].

According to the Order of Rostekhnadzor of May 13, 2015, No. 188 [6], the frequency of accidents during depressurization of tanks due to local leaks from connecting hoses is estimated to be $1 \times 10^{-6}$ year$^{-1}$ for tanks under overpressure and $1 \times 10^{-6}$ year$^{-1}$ for tanks under atmospheric pressure.

2. Discussion of the results
Analysis of possible emergency situations during oil-handling operations was performed using the TOXI+Risk software package and regulatory documents [7-8]. Calculations in the TOXI module showed that emergency depressurization of a railway tank with a gasoline volume of 40 m$^3$ may cause instantaneous ignition, resulting in a pool fire. If there occurs no instantaneous ignition, delayed ignition may develop with the formation of a fuel-air mixture cloud or without the formation of a fuel-air mixture cloud. If a cloud has formed, a fuel-air mixture explosion or a flash fire may occur, resulting in a pool fire, as in case of ignition without the formation of a fuel-air mixture cloud. In the absence of ignition, there will be scattering without ignition.

Fuel scattering without ignition (0.53) and a pool fire (0.03) have the greatest conditional probability,
a fire-flash (0.002) has a smaller conditional probability, a fuel-air mixture explosion is unlikely.

Let us analyze the most probable emergency events - scattering in the atmosphere - occurring without ignition with a higher conditional probability (0.53).

It is important to note that gasoline is a flammable fuel and can spread in the environment, creating zones with different explosive concentrations. Thus, the lower explosion limit (LEL for gasoline - 0.2792 kg/m$^3$), as established by the calculations, extends to 17 m downwind and has a maximum half-width of 84 m at a distance of 16 m from the epicenter, and the upper explosion limit (UEL for gasoline - 0.25826 kg/m$^3$) extends to a distance of 4 m downwind and has a maximum half-width of 58 m at a distance of 4 m from the epicenter.

Atmospheric stability is of substantial significance. Thus, the greatest spread of the cloud under the worst scattering conditions (stratification F, at night, wind speed 2-3 m/s, with low cloudiness) with the lower explosion limit (LEL) is observed at a distance of 17 m.

The analysis of the dependency of the gas cloud parameters on the time of its spread in the atmosphere showed that in the first period of time as a result of gravitational properties the cloud is found in the surface layer (up to 100 s). After 200 s, the cloud actively spreads in the atmosphere, reaching a distance of up to 100 m, and after 600 s - a distance of 700 m, whereby the highest concentration of gasoline in the core of a gas cloud of 44 kg/m$^3$ is reached within 100 seconds of fuel ejection into the surrounding space.

The resulting vapor-air mixture is hazardous and can be ignited in the presence of an ignition source. In such an event, the danger of ignition arises in the first seconds/minutes of the spill, especially when the explosion limits are reached.

To quantify the mass of gasoline-air clouds constituting an explosion hazard, we carried out its calculation using the TOXI software module “Explosive Mass Calculation”. The calculation of the explosive mass of a vapor-air cloud showed that already at the 10th second of scattering, an explosive mass of 0.34 kg was formed at an insignificant distance from the epicenter. The maximum explosive mass (the calculation time limit is 900 s) is 31.846 kg with the formation of an air-vapor cloud after 100 s (see Figure 1), which can lead to a flash and subsequent development of a pool fire or a fuel-air mixture explosion, as the danger of ignition remains for a long time (over 1000 s).

The presence of an explosive mass can lead to the ignition of spilled gasoline with the development of a pool fire. Let us consider forecast events for some scenarios.

Initial data for modeling of probable events: accident scenario - depressurization of equipment (railway tank) with a gasoline volume of 40 m$^3$, which is 23,680 kg (when filled by 0.8), ambient temperature 14 °C (287 K) (average summer temperature according to meteostatistics in the region); wind direction in the territory of the facility is south easter, the surface of the spill is unconfined and concrete. The accident was modeled for the worst scattering conditions, i.e. with minimal horizontal and vertical movement of the atmosphere (wind speed 1-2 m/s, stratification F). The time of the
accident liquidation is equal to the time of the liquid phase expiration, i.e. 3600 seconds. The pressure in the equipment is equal to the saturated vapor pressure.

The results of calculations for the emergency event “Pool Fire” carried out according to the method [2], with a gasoline spill area of 640 m$^2$ ($d_{eff} = 28.55$ m) are presented in Table 1.

### Table 1. Data calculated for the damaging factors of a pool fire on the gasoline handling rack.

| Criterion                                      | Intensity of thermal radiation, kW/m$^2$ | Radius of the affected area, m |
|------------------------------------------------|------------------------------------------|-------------------------------|
| Rubber ignition                                | 14.8                                     | 29.4                          |
| Wood ignition                                  | 13.9                                     | 30.88                         |
| Intolerable pain after 3-5 seconds             | 10.5                                     | 37.50                         |
| Intolerable pain after 20 seconds              | 7                                        | 47.09                         |
| Safe for people in canvas clothing             | 4.2                                      | 60.0                          |
| No negative consequences                      | 1.4                                      | 96.24                         |

In this scenario, we studied the change in the intensity of thermal radiation depending on the distance, and the probability of death of a person from the flame thermal radiation. It has been shown that the risk of getting burns persists at a distance of up to 47 m with an intensity of thermal radiation of 7-10.5 kW/m$^2$, and the risk of fatal injury - at a distance of up to 37 m from the epicenter of the fire. Distance safe for personnel - 97 m and more.

### Table 2. Data calculated for the effects of an air shock wave after an explosion of fuel-air mixture vapors.

| Criterion                                                                 | Overpressure, kPa | Impulse, kPa | Radius of the area, m |
|---------------------------------------------------------------------------|-------------------|--------------|-----------------------|
| Criterion: overpressure                                                   |                   |              |                       |
| Average damage to buildings                                              | 28                | 3.44         | 15.05                 |
| Operating personnel will be seriously damaged with possible fatal outcome | 24                | 2.68         | 19.35                 |
| due to shrapnel, building debris, burning objects, etc. There is a       |                   |              |                       |
| 10% chance of eardrum rupture                                             |                   |              |                       |
| Possible temporary loss of hearing or injury due to secondary effects of   |                   |              |                       |
| a blast wave, such as a building collapse, and a tertiary effect of body  |                   |              |                       |
| transfer                                                                  |                   |              |                       |
| Moderate damage to buildings (damage to internal partitions, frames, etc.)| 12                | 1.13         | 45.96                 |
| No fatal outcome or serious damage is guaranteed with high reliability   | 5.9               | 0.619        | 83.7                  |
| Lower threshold of damage to a person by pressure wave                    | 5                 | 0.544        | 95.26                 |
| Minor damage (partially broken glazing)                                  | 3                 | 0.358        | 144.58                |
| Criterion: pressure - impulse                                             |                   |              |                       |
| Border of the significant damage area                                     | 14.71             | 1.424        | 36.35                 |
| Complete destruction of the glazing                                      | 7.02              | 0.7051       | 73.43                 |
| Border of the minimal damage area                                         | 2.5               | 0.307        | 168.88                |
| 10% destruction of the glazing                                           | 2.01              | 0.250        | 205.04                |

Initial data: Modeling of the consequences of possible explosions of the fuel-air mixture in the
probable scenario (depressurization with gasoline spill from the railway tank) is carried out with the following initial data: gasoline sensitivity class - medium sensitive substance, gasoline concentration equal to stoichiometric (0.07329 kg/m³), explosive mass - 32 kg, surrounding space - average congestion, the cloud is at the soil surface, height of the spill - 0.01 m, specific heat - 46.74 MJ/kg. Calculations for the damage criteria are presented in Table 2.

It was possible to identify the dependency of the overpressure and the impulse of the wave on the distance. The average damage to buildings continues up to 15 m from the epicenter of the accident, and the border of the significant damage area - up to 36.35 m.

Thus, with an overpressure of 16-24 kPa at a distance starting already from 15 m, the operating personnel will be seriously damaged with possible fatal outcome due to shrapnel, building debris, burning objects. There is also a 10% chance of eardrum rupture.

3. Conclusion
Predictive analysis of events associated with the depressurization of the tank showed the probability of the occurrence and development of fires resulting from the spread of clouds of flammable gases with concentrations corresponding to the concentration limits of ignition. The development of ignition with a pool fire or the propagation of an air shock wave as a result of an explosion of the fuel-air mixture will lead to destruction and damage to the personnel operating the equipment.

References
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