Physical and mathematical measurements of potential hazard during storage of diesel fuel at the tank battery

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Abstract. The article briefly describes the results of calculations of probable potential accidents (emergencies) at a technical facility designed for storing diesel fuel at a tank battery and their consequences for humans and the environment. The calculations considered the most important parameters: the amount and hazard class of substances, the volume, and area of industrial premises, temperature and pressure fluctuations, the distance of personnel from the damaging factor, etc. It was revealed that such types of accidents as an explosion of a fuel-air mixture, a pool fire, jet fire, an explosion inside equipment, an explosion inside a building are possible at this enterprise. As a result of calculations, it has been established that the most likely accident will occur in case of partial depressurization of the pipeline and the formation of the pool fire, the number of the forecasted casualties is 1 person.

1. Introduction
The enterprises of the oil refining industry produce and store many petroleum products of different brands of various purity and quality classes \cite{1; 2; 3}. The production and processing of petroleum products become more complicated with the continuously increasing rate of extraction of raw materials \cite{4; 5; 6}. Accidents that occur during storage and processing have serious consequences. Special reservoirs for the collection and preparation of petroleum products are widely used and are the main facilities of the warehouses of transport enterprises, heat and power plants, construction, and industrial enterprises \cite{7; 8}. In this regard, there is an acute problem of ensuring safety during the transportation and storage of petroleum products.

The planned use of the container pre-defines its volume and design features. Emergencies can arise in case of various types of depressurization of equipment and tanks, overflows, violation of operating rules, and during repair work. Prevention of emergencies by developing physical and mathematical models based on accurate measurements is the most important task for engineers \cite{9; 10}. The fact that petroleum products have the highest class of fire and explosion hazards and considering the intensification of all technological processes make the existing issue more actual \cite{11; 12}. 
2. Materials and methods
The target object (storage of diesel fuel at the Krasny Neftyannik oil depot in St. Petersburg) has the warehouse of petroleum, oil, and lubricants (POL), which is used for receiving, storing, preparing, and continuous supply of consumers with diesel fuel.

Diesel fuel is pumped through process pipelines (aboveground and underground) from reservoirs to storage tanks, from which it is delivered to consumers by pumping.

Considering the location of sites, technological equipment, utilities, and the specifics of production, the target enterprise can be divided into several components:

The tank battery consists of 3 metal tanks with a volume of 10,000 m$^3$ each, vertically placed and surrounded by the earth embankment with dimensions of 60x140x1.7 m (with a partition separating one tank).

The station for pumping fuel and lubricants (pumping station for light oil products with pumps (4 pcs.) and coarse filters (4 pcs.)).

When carrying out work on the territory of the enterprise - at the sites of railway overpasses, in the tank battery, in the premises of the pumping station of fuels and lubricants, where hazardous substances (fuel oil, diesel fuel, gasoline, kerosene, technical oils) are processed, there can be up to 9 people. The number of the largest working shift is 22 people.

- Unit 1 - pipeline in the pumping station.
- Unit 2 - a pipeline for transportation of diesel fuel from the pumping station to the storage tank.
- Unit 3 - tank battery - vertical tank RVS-10000.
- Unit 4 - a pipeline for transportation of diesel fuel from the storage tank to the vehicle filling station.

All units belong to the category of explosive and fire hazardous objects.

There were no accidents at the target object during its operation. As a result of the analysis of known accidents with diesel fuel at other similar facilities, the main causes of emergencies were identified:

- the destruction (depressurization) of technological equipment, pipelines, and fittings, failures of the facility's emergency protection systems;
- the errors, delays, inaction of personnel in normal and emergencies, unauthorized actions of personnel.

The most common emergency is pool fires. They can be caused, first, by complete or partial depressurization of tanks and pipelines.

A cloud of a fuel-air mixture (FAM) occurs the following way:

- depressurization of equipment containing a flammable liquid (diesel fuel - diesel fuel) occurs;
- a DF pool is formed;
- at an ambient temperature exceeding the flashpoint of a flammable liquid (FL), the pool evaporation starts;
- the diesel fuel vapors are mixed with air to such an extent that their concentration reaches the ignition level;
- the FAM is formed.

The calculation is made according to the availability of the following initial data:

- $m_c$ - mass of combustible matter contained in the FAM cloud, kg
- $q_c$ – specific heat of combustible gas, MJ/kg;
- $c_c$ – concentration of combustible matter in the FAM cloud, kg/m$^3$;
- $C_{st}$ – stoichiometric concentration of a combustible substance mixed with air, kg/m$^3$;
- combustion class (1÷6);
speed of sound in air – 331.46 m/s;
living body weight – 80 kg;
aggregate state of FAM;
atmospheric pressure – 1 atm;
the number of distances from the center of the cloud - no more than 9.
Diesel fuel belongs to the 3rd class of medium power sensibility matters.

3. Results and discussion
According to calculations, the following types of accidents are possible at this facility:

- **Formation of a cloud of a fuel-air mixture (FAM) (scenario C₁):**
- Depressurization → spillage → evaporation of the liquid phase → formation of a cloud of fuel-air mixture → deflagration → impact of an air-blast wave (air blast).
- **Instant ignition of the pool (scenario C₂):**
- Depressurization → pool → pool fire (jet fire) → thermal impact on people and buildings.
- **Pool fire with delayed ignition (scenario C₃):**
- Depressurization → pool → pool fire (jet fire) → thermal impact on people and buildings.
- **Explosion inside equipment (scenario C₄):**
- Formation of a vapor-gas phase (VGP) and the appearance of an ignition source → explosion inside equipment → formation of air-blast and fragmentation of equipment → impact of air-blast and equipment fragments on people.

The most likely scenario is $C_{3.2} = 1.35 \times 10^{-5}$ 1/year: Partial depressurization of the pipeline → pool → pool fire → thermal impact on people and buildings.

The most dangerous scenario is $C_{1.3} = 2.74 \times 10^{-8}$ 1/year: Depressurization → spill → LF evaporation → formation of a cloud of fuel-air mixture → deflagration → air-blast impact.

The example of the results of calculating the amount of diesel fuel involved in the accident for unit 3.

*For the “pool fire” scenario:*

The amount of substance involved in the creation of damaging factors and the accident is the same.

- In the case of partial depressurization ($⌀$ hole = 25 mm), the mass of liquid involved in the accident during a pool fire is 426 600 kg.
- With a complete depressurization, the entire mass of the substance in the container will participate in the pool fire of, i.e., $m = 6640000$ kg.

*For the “deflagration with afterward air-blast wave impact” scenario:*

- In case of partial depressurization ($⌀$ hole = 25 mm).
- The mass of the diesel fuel involved in the accident is equal to the mass involved in the accident of the pool fire, i.e., $m = 426600$ kg.

The mass of flammable liquids vapors entering the open space during the time of complete evaporation, but not more than 3600 s: $m_i = 464$ kg. The mass of the substance involved in the creation of the damaging factor (air-blast wave): $m' = 46.4$ kg.

- With complete depressurization, the explosion of the FAM will involve the entire mass of the substance that was in the container, i.e., $m = 6640000$ kg.

*For the “explosion inside the equipment” scenario:*

Full mass of gas: $C = 5441.6$ kg.
The mass of the substance involved in the creation of the damaging factor (air-blast wave): \( m' = 1632.5 \text{ kg} \).

Specific explosion energy of gas mixture - \( Q = 43590000 \text{ J/kg} \).

Since the nature of the surrounding space largely determines the rate of explosive transformation of the FAM cloud and, consequently, the parameters of the shock wave, the geometric characteristics of the surrounding space are divided into types by the degree of clutter. In this case, we have a medium-cluttered space - stand-alone technological units and the tank battery.

According to the class of combustible substance and the type of surrounding space, the mode of explosive transformation is deflagration, i.e., combustion with a high speed of propagation of the flame front. According to the mode of explosive combustion of the substance, we determine the range of velocities of the flame front propagation: \( V_g = 150-200 \text{ m/s} \). Assessment of the aggregate state of FAM: the mixture is heterogeneous if more than 50% of the fuel is contained in the cloud in the form of droplets, otherwise the FAM is gaseous. In this case, the mixture is homogeneous.

According to calculations, during the combustion of the gas-vapor-air mixture in the pumping room, an overpressure of 10.76 kPa may develop, which will lead to moderate damage to buildings (damage to internal partitions, frames, doors, etc.).

When a closed container with a liquefied gas or liquid enters the fire, the contents of the reservoir may be heated to a temperature significantly higher than the normal boiling point, with a corresponding increase in pressure. Due to the heating of the non-wetted walls of the vessel, the ultimate strength of their material decreases, because of which, under certain conditions, it becomes possible to rupture the reservoir with the appearance of pressure waves and the formation of a "fireball". The rupture of the reservoir in the fire with the formation of pressure waves was called BLEVE (Boiling Liquid Expanding Vapor Explosion).

According to calculations at the target object, the possibility of BLEVE occurrence \( \delta = 0.32 < 0.35 \), therefore, it does not occur.

The conditional probability of human injury during jet combustion was determined: the length of the jet with partial depressurization of the pipeline of any block from the pumping station to the reservoir is \( L_j = 35.3 \text{ m} \).

When determining the number of injured people, the following circumstances were considered:

- location of people;
- location of personnel and neighboring equipment near and at the epicenter of the accident;
- presence of personal and collective protection equipment.

Assessment of the likelihood of causing harm to personnel is reduced to the determination of individual, collective, and social risk.

Individual risk is the frequency of injury to an individual because of exposure to the studied hazards. Collective risk determines the expected number of casualties because of an accident at a facility for a certain time.

Social risk characterizes the severity of the consequences (catastrophic) of the implementation of hazards.

Identifying potential risk: \( R_{pot} = 8.84 \times 10^{-5} \text{ year}^{-1} \)

Identifying individual risk: \( R_{ind} = 1.95 \times 10^{-5} \text{ year}^{-1} \)

Identifying collective risk: \( R_{coll} = 1.7 \times 10^{-5} \text{ year}^{-1} \)

Frequency of occurrence of accidents with 3 injured persons: \( C_{3\text{pers.}} = 3.83 \times 10^{-5} \)

Frequency of occurrence of accidents with 2 injured persons: \( C_{2\text{pers.}} = 4.71 \times 10^{-5} \)

Frequency of occurrence of accidents with 1 injured person: \( C_{1\text{pers.}} = 8.12 \times 10^{-5} \)

It can be concluded that in case of an accident, the maximum number of casualties is 1 person since the rest of the personnel is outside the danger zone.

The spread of damaging factors outside the territory of the enterprise is unlikely, because, within the zone area of damaging factors, there are quite modern measuring systems, at the facility, a timely
technical examination of vessels and pipelines operating under pressure is carried out, a constant check is made for the tightness of technological equipment and pipelines.

4. Conclusions

The “event trees” were built, according to which, certainly, such types of accidents as FAM explosion, pool fire, jet fire, an explosion inside equipment, an explosion inside a building are possible at this enterprise. As a result of calculations, it was established that the most probable accident will occur with partial depressurization of the pipeline and the formation of a pool fire with a probability of 1 casualty.

The assessment of the industrial safety and risk of storage of diesel fuel at the target object was carried out. The value of the individual risk is \( R = 1.95 \times 10^{-5} \), which is higher than the standard value of \( R_s = 1.0 \times 10^{-6} \), therefore, the level of ensuring the safety of people in case of fires does not meet the requirement. The social risk value is \( S = 9.5 \times 10^{-5} > 10^{-7} \).

The most significant factors influencing the risk indicators are:

- timeliness of taking measures to warn personnel about emergencies and making appropriate decisions;
- proper implementation of duties, strict adherence to safety requirements when working with hazardous substances;
- the amount of substance escaped from the emergency unit with full or partial depressurization.

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