Industrial and ecological safety analysis for modeling oil and petroleum products spills in the Arctic waters of the Kola Bay

A A Katansky¹, E E Minchenok², N G Zhuravleva³, Ye Yu Aleksandrova⁴ and A A Trotsenko⁴

¹ Rostov Institute for Protection of Entrepreneurship, 2/104 Serzhantova street, Rostov-on-Don, 344029, Russia
² Murmansk State Technical University, 23 Sportivnaya street, Murmansk, 183010, Russia
³ Murmansk Marine Biological Institute, 17 Vladimirskaya street, Murmansk, 183010, Russia
⁴ Murmasnk Arctic State University, 9 Kommuny street, Murmansk, 183038, Russia

E-mail: trotcenko2007@yandex.ru

Abstract. The paper analyses the industrial safety of the coastal and water areas of the Kola Bay of the Barents Sea when modeling the spill of oil or petroleum products. It gives a brief description of the methods and stages of liquidation of oil spills in the water and coastal areas as well as the main causes of accidents. It presents the results of physical and mathematical calculations in theoretical modeling of oil and petroleum products spills, namely: fire risk analysis, calculation of the minimum amount of combustible substance with partial destruction of the tank, calculation of probable areas of hazard boundary during an accident at the pump station, results of calculating the probability of explosion at the pumping station, and individual, collective and social risks. The most likely scenario is an event with partial depressurization (the probability will be 3.9\times10^{-5} \text{ 1/year}): partial depressurization of the tank with liquid oil or petroleum products → oil slick formation → oil slick fire → personnel and equipment present in the hazardous area → exposure of people to thermal radiation. It was found that a minimum of 1182 kg of spilled crude oil is required for uncontrolled combustion to occur with an intensity of thermal radiation of not more than 4.2 kW/m² m. The time to reach the maximum volumetric average temperature (894 K) in an accident at the pumping station is 136.8 minutes. In these calculations, the individual risk $R_{\text{ind}} = 3.31\times10^{-5} \text{ 1/year}$ exceeds the regulatory standard, which shows an urgent need to reduce this risk. The collective risk is: $R_{\text{col total}} = 1.98\times10^{4} \text{ persons/year}$. Regarding the social risk, we can conclude that the minimum number of injured people will be three in case of an accident at the pump station or during the spill of oil or petroleum products into the Kola Bay, taking into account the fire development. The presented theoretical accident models will reduce the risk of major accidents involving petrochemical pollution of environmental objects, thereby preventing environmental damage, and the problem of the management of large oil spills at various facilities and technological systems of industrial enterprises will be solved.

1. Introduction
According to estimates cited annually by various world organizations that the main reason for the most widespread local pollution of the aquatic environment with oil products is accidental spills during tanker...
transportation [1, 2]. Oil spills in the water area can lead to disastrous consequences, causing significant environmental damage to the coastal area. It is generally accepted that the thickness of the oil layer on water, at which the combustion is possible, is at least 1-2 mm. In real conditions, the possibility of ignition largely depends on factors such as:

- oil composition (light distillate content)
- individual physical-chemical properties of the oil grade (density, viscosity, dissolubility and ability to form emulsions with water)
- volumes and speed of oil intake, time of its contact with water
- sea hydrometeorological conditions
- presence of foreign objects on the water surface (garbage, equipment, algae).

Up to the present, no sufficiently accurate model has been developed to describe the possibility of ignition of oil spills on the water surface, considering all the above factors and the modes of oil slicks spreading on the sea surface. The fire and explosion hazard properties of oil slicks are also of considerable interest in terms of the possibility of their elimination by burning. This method can be an effective means of controlling free oil, especially in open waters and in ice conditions and from the point of view of analyzing the possibility of ignition and burning of oil in the period from the time of the spill to the day until the oil layer has not yet dispersed [5, 6, 7].

Crude oil is a mixture of chemicals containing hundreds of components. In the case of an oil leak, the conditions for its interaction with the environment radically change. Oil spilled on water forms a thin layer, in which every kilogram of oil covers on average several square meters of surface area contacting with water and air. The interaction of the oil slick with the environment takes place in this layer, it results in changes in oil mass and properties, and the slick itself is destroyed. The intensity of interaction increases with wind speed, i.e. evaporation of the fractional composition of oil and petroleum products is important for assessing the slick as a skimming object.

The surface tension of frictional brake, which depends on the influence of wind and the sun on the spill, affects the process of oil scattering across a water surface, for example, after 24 hours, about a quarter of all oil is removed from the surface due to evaporation and other processes. Evaporation of volatile oil components into the air increases the density of the remaining oil and disperse in the water layers. With a moderate sea state, the oil-water emulsions containing up to 80% of water are created within 2 hours. The density and viscosity of oil are its most important properties that affect the nature of pollution and the choice of skimming methods.

Oil spill response has 6 stages:

- Identification and notification;
- Assessment and operational response (taking safety measures for the vessel and the source of a spill);
- Oil spill containment (control of free oil spreading over large areas) and countermeasures.
- Oil spill response with a selected method;
- Collection of skimmed oil and waste products;
- Recycling of collected oil.

The main method of eliminating oil spills in the sea is mechanical collection. Mechanical collection and containment of the spill with booms are possible with sea waves of 3 points and wind forces of up to 5 points. In other cases, other oil spill response methods are used when mechanical oil recovery is not possible and when the spilled oil poses a real threat to human settlements and other important facilities on the shore. An oil slick can travel over long distances. A wide range of technical equipment is required to effectively respond to a spill that can influence the situation depending on changing sea and oil states.
Design solutions ensure the reliable operation of the pipeline throughout the entire period of operation. However, in practice accidents cannot be avoided completely. The main causes of the accident are:

- low-quality construction;
- deviation from design projects;
- internal corrosion of pipelines and devices;
- mechanical damage to oil carriers;
- violation of safety rules during oil handling.

The following are the local oil spill response areas for the following situations [11, 12]:

- spill on the surface water body
- spill on the surface of the river with a flow rate of more than 0.5 knots
- spill on the surface of the river with a flow rate of less than 0.5 knots
- spill on a plant-filled water surface
- spill on land
- spread of oil cans
- oil on machine parts
- oil on filters
- spill on floor and solid surfaces
- oil in draining systems
- spill on forest land

About two hundred types of sorbents are produced to eliminate oil spills: synthetic, bioorganic, organic, natural organic and organic mineral. The quality of sorbents is determined by their oil adsorption capacity, hydrophobic properties, buoyancy after oil sorption, the possibility of oil desorption and sorbent recycling process.

2. Results of modeling emergency scenarios for oil and petroleum products spills in the Kola Bay

Fire risk analysis was performed for an emergency at the oil terminal located on the shore of the Kola Bay. According to the statistics, the main causes of accidents at this facility are:

- failures (equipment malfunctions) - 50% of all cases;
- human errors - 30%.

Loss of equipment containment leads to an emergency process in which hazardous substances and process equipment are involved in processes not covered by the regulations - explosions and fires. In this case, the probability of the most dangerous scenario is \(4.1 \cdot 10^{-5}\) 1/year: complete depressurization of the tank with liquid oil or other oil products → the formation of an oil spill on the surface of the water and in the water layers → evaporation and the formation of a cloud of fuel mixture (FM) above the surface water → FM cloud explosion → shockwave affecting personnel and equipment.

However, the most likely scenario is an event with partial containment loss (the probability will be \(3.9 \cdot 10^{-5}\) 1/year): partial depressurization of the tank with liquid oil or petroleum products → oil slick formation → oil slick fire → personnel and equipment are in the danger area → people are exposed to thermal radiation [13, 14].

3. Physical-mathematical models and calculations used in assessing the risks of oil spills

The following mathematical models can be used at the target facility to calculate the areas within hazard boundary during oil and petroleum product spills in the Kola Bay: calculate the minimum amount of
combustible material in case of partial destruction of the tank (i.e., an opening of at least 25 mm spilling oil into the Kola water area). The liquidation time of the accident is conditionally 30 minutes. It was found that uncontrolled combustion will occur with a minimum spill of crude oil mass of $m = 0.0025 \cdot 788 - 600 = 1182$ kg [14, 15].

**Calculation of the intensity of thermal radiation during the spill of crude oil in the Kola Bay.** The calculation is carried out to determine the size of the areas of exposure to thermal radiation on humans and materials ($q$, kW/m²). According to these calculations, it was found that the thermal radiation impact distance, i.e. between a person and the ignition zone of crude oil, does not exceed 4.2 kW/m² m.

**Calculation of probable areas within hazard boundary in case of an accident at a pumping station.** Since the pumping facility is located indoors on the shore of the Kola Bay, therefore, the calculation of probable areas must be carried out considering the important initial data and their subsequent substitution into the calculation formulas:

- Pump station space: $V = 1060$ m³
- Floor area: $S_{floor} = 200$ m²
- Aperture area: $A_1 = 1.2$ m², $A_2 = 2.4$ m², $A_3 = 20.25$ m², $A_4 = 20.25$ m²
- Aperture height: $h_1 = 2$ m, $h_2 = 2$ m, $h_3 = 3$ m, $h_4 = 1$ m.

The total amount of fire load reduced to wood is $4.68 \cdot 10^4$ kg, which corresponds to a fire load $q = 20$ kg/m²

Total area of pump station apertures: $A = \sum A_i = 44.1$ m²

The corrected height of station apertures:

$$h = \frac{\sum A_i \cdot h_i}{A} = 1.05 \text{ m}$$

Aperture capacity of the room:

$$AC = \sum A_i \cdot \frac{h_i^{0.5}}{S} = 0.232 \text{ m}^{0.5}$$

Amount of air required to burn 1 kg of fire load material

$$V_0 = \frac{\sum V_{oil} \cdot P_i}{\sum P_i} = \frac{4.2 \cdot 4.68 \cdot 10^4}{4.86 \cdot 10^4} = 4.2 \text{ nm}^3/\text{kg}$$

Specific critical amount of fire load:

$$q_{cr} = \frac{4500 \cdot AC^3}{1 + 500 \cdot AC^3} + \frac{V_0^{0.333}}{6 \cdot V_0} = \frac{4500 \cdot 0.23^3}{1 + 500 \cdot 0.23} + \frac{1060^{0.333}}{6 \cdot 4.2} = 8.171 \text{ kg/m}$$

Specific fire load:

$$q_k = \frac{\sum P_i \cdot Q_{Hi}^p}{(6 \cdot S - A) \cdot Q_{Hg}^p} = 80.535 \text{ kg/m}^2$$

$q_k > q_{cr, \text{critical (tabulated value)}}$ therefore, there will be a fire regulated by ventilation system of the room. Maximum volumetric average temperature at the stage of medium fire:

$$T_{max} = 940 \cdot e^{4.7 \cdot 10^{-3} (q_{30})} = 940 \cdot e^{4.7 \cdot 10^{-3} (20 - 30)} = 897 \text{ K}$$

Characteristic fire duration:

$$q_k = \frac{\sum P_i \cdot Q_{Hi}^p}{6285 \cdot A \cdot \sqrt{h}} \cdot \frac{n_{cp} \cdot \sum P_i}{6285 \cdot 44.1 \cdot \sqrt{1.05}} = \frac{4.68 \cdot 10^{-4} \cdot 13.8 \cdot 2.4 \cdot 4.68 \cdot 10^4}{2.4 \cdot 4.68 \cdot 10^4} = 2.28 \text{ h}$$

Time to reach maximum volumetric average temperature:
$t_{\text{max}} = t_e = 136.8 \text{ min}$

Maximum averaged surface temperature of the surface:

$$T_{W_{\text{max}}} = 940 \cdot e^{5 \cdot 10^{-30}} = 940 \cdot e^{5 \cdot 10^{-20-30}} = 894 \text{ K}$$

### Table 1. The main results of the calculation of the fire temperature in the pump station

| Event causing the accident | Index                                      | Value |
|---------------------------|--------------------------------------------|-------|
| Loss of containment of a pump and flang connections | Maximum volumetric average temperature, $C^0$ | 624   |
|                           | Maximum value of average aperture temperature, $C^0$ | 621   |
|                           | Time to reach the maximum volumetric average temperature, h | 136.8 |

The results of calculating the probability of an explosion at a pumping station (gauge pressure). Initial data:

Free space in the station $V_k = 865 \text{ m}^3$

Maximum pressure developed during the combustion of a stoichiometric gas-air mixture $P_{\text{max}} = 900 \text{ kPa}$.

Initial pressure $P_0 = 101 \text{ kPa}$.

Mass of hot gas released as a result of a design accident $m = 694 \text{ kg}$

Molar mass of arctic diesel fuel $M = 172.3 \text{ kg/kmol}$

Estimated temperature at pump station $t_e = 21^\circ\text{C}$

Molar volume $V_0 = 22.413 \text{ m}^3/\text{kmol}$

Stoichiometric coefficient of oxygen in the reaction $\beta = 12.5$

Steam density at estimated temperature:

$$p_{gp} = \frac{M}{V_0 \cdot (1 + 0.00367 \cdot t_e)} = 7.18 \text{ kg/m}^3$$

Stoichiometric vapor concentration of fuel mixture:

$$C_{ct} = \frac{100}{1 + 4.84 \cdot \beta} = 1.626\%$$

Gauge pressure:

$$\Delta p = (p_{\text{max}} - p_0) \cdot \frac{m \cdot z}{v_c \cdot p_{gp}} \cdot \frac{100}{c_{ct}} \cdot \frac{1}{K_H} = (900 - 101) \cdot \frac{694 \cdot 0.3}{865 \cdot 7.18} \cdot \frac{100}{1.626} \cdot \frac{1}{3} = 550 \text{ kPa}$$

So, during a fire at a pumping station on the shore of the Kola Bay, pressure can go over 550 kPa, which will lead to the complete destruction of the building and the death of all people in it.

When determining the possible minimum number of injured persons, we consider such indicators as the workplaces of personnel, the position of personnel and equipment from the epicenter of the accident, and the presence of personal protection equipment.

*Individual risk* - the frequency of human injuries resulting from the casualty-producing elements of the accident:

$$R_{\text{ind}} = \sum_{k=0}^{n} Q_{ni} \cdot Q_i \cdot P_{npi}$$

where $R_{\text{ind}}$ – individual risk, 1/year.
Q_{ni} – conditional probability of human injury during the implementation of the i\textsuperscript{th} accident scenario;
Q_{i} – probability of the i\textsuperscript{th} accident scenario during a calendar year;
P_{npi} – probability of a person being present in the area of hazard area for the i\textsuperscript{th} scenario;
n – number of accident scenarios.

The probability of presence of work personnel in the hazardous area during a possible accident is determined according to the following formula:

\[ P_{npi} = \frac{\tau_{i} \cdot n_{i}}{T} \]

where \( \tau_{i} \) – time of exposure to hazardous factors for a person per one shift, h;
T – hours per year;
n\textsubscript{i} – number of work shifts per year
R\textsubscript{ind} = 3.31 \times 10^{-5} \text{ 1/year}.

In this case, the individual risk exceeds the regulatory standard, therefore, it is necessary to develop guidelines for reducing R\textsubscript{ind}, for example, engineering and technical measures decreasing the likelihood of an accident and the intensity of the hazardous factors.

**Collective risk** - the expected number of injured people as a result of possible accidents per time unit:

\[ R_{col} = \sum_{i=1}^{n} Q_{i} \cdot t \]

where R\textsubscript{col} – collective risk, person/year;
Q_{i} – probability of the i\textsuperscript{th} accident scenario during a calendar year;
N_{i} – number of casualties during the i\textsuperscript{th} accident scenario.
Collective risk: R\textsubscript{col total} = 1.98 \times 10^{-4} \text{ (person/year)}.

As for the social risk, we can conclude that the minimum number of injured people equals three for any accident at the pump station or during the spill of oil or petroleum products into the Kola Bay, taking into account the fire development.

The calculation results for modeling the spill of oil and petroleum products in the Kola Bay will allow:

- to develop and patent new materials and technological solutions aimed at the quick and efficient management of oil spills;
- to develop process procedures for the production of new materials for integrated oil spill clean-up of the water and coastal areas;
- to develop manufacturing capabilities for producing new materials for future implementation at industrial facilities and in units of the Ministry of Emergencies of Russia in the Murmansk Region;
- to reduce the risk of major accidents involving petrochemical pollution of environmental objects, thereby preventing environmental damage and saving funds of the Russian Ministry for Emergencies. At the same time, the problem of management of large oil spills at environmental compartments and industrial process systems of enterprises will be solved [4, 8, 9, 10].

4. Conclusions
The most likely scenario is an event with partial depressurization (the probability is 3.9 \times 10^{-5} \text{ 1/year}). It was found that a minimum of 1182 kg of spilled crude oil is required for uncontrolled combustion with an intensity of thermal radiation of not more than 4.2 kW/m\textsuperscript{2} m. The maximum volumetric average temperature of 894 K (or 621 °C) will be reached at a pumping station in about 136 minutes. The individual risk R\textsubscript{ind} = 3.31 \times 10^{-5} \text{ 1/year} exceeds the regulatory standard, which shows an urgent need to reduce this type of risk. The collective risk is R\textsubscript{col total} = 1.98 \times 10^{-4} \text{ persons/year}. Regarding the social risk, we can conclude that the minimum number of injured people will be three in case of an accident at the
pump station or during the spill of oil or petroleum products into the water area of the Kola Bay, taking into account the fire development.

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