Methodology for Evaluating a Prevented Damage in Accidents at Energy Saturated Objects

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Abstract. The topic of low-power nuclear power plants has been relevant for more than 50 years. They allow you to conduct electrical energy in remote areas, such as, for example, the Arctic, and to build stations with the possibility of mobile regulation in cases of emergency. Currently, the state corporation Rosatom has launched a broad propaganda about the prospects of these nuclear power plants and has stepped up the construction of the first floating nuclear thermal power plant, which is one of the variants of this type of nuclear power plants. The idea of creating this project has generated a mass of protests from environmental organizations. In this paper, the scenario of a beyond design basis accident at a floating nuclear power plant is considered. Calculation of the damaging factors of this accident. The calculation of prevented damage was made using the existing methodology with some changes made for convenience of calculation, and a formula was introduced for comparing the costs of measures to prevent damage with the magnitude of this damage. The improved methodology can be used in the EMERCOM of Russia system for forecasting emergencies at the facility level. The introduction of this methodology and its practical application for the assessment of prevented damage will make it possible to predict the consequences of the occurrence of emergency situations on energy-saturated objects, objects with a massive presence of people.

1. Introduction

Radiation accident - an accident at a radiation-hazardous facility, leading to the release or release of radioactive substances and (or) ionizing radiation beyond the limits provided by the project for the normal operation of the facility, in quantities exceeding the established safety limits of its operation [1].

At the moment, the first in the world floating nuclear power plant “Akademik Lomonosov” (hereinafter FENP) is preparing for launch. [2]. The idea of creating this project has generated a mass of protests from environmental organizations. Many experts believe that such a nuclear experiment could end disastrously not only for the region where the FNPP is located, but also for the whole of Russia. Therefore, it is necessary to consider the issue of a possible radiation accident at the facility and assess its consequences. Currently, to assess the actual losses, there is a “Unified interdepartmental methodology for assessing damage from technogenic, natural and terrorist emergencies, as well as classifying and accounting for emergencies” [3]. This methodology is designed to predict damage at all levels (federal, regional, territorial, municipal and facility) of the territorial subsystems of the Unified State System for the Prevention and Liquidation of Emergency Situations (ESPS).
The existing technique needs improvement. The disadvantages of this technique are that it is not developed at the object level. This technique is designed to assess the consequences of an accident that has already occurred and does not allow predicting the damage from a possible accident in the future. Also, the technique makes it impossible to compare the costs of preventive measures with damage from emergency situations.

In this regard, it is necessary to draw up a methodology for assessing the prevented damage from accidents at energy-saturated facilities.

The purpose of this work is to assess the damage prevented during a radiation accident at a floating nuclear power plant.

To achieve this goal it is necessary to solve the following tasks:
1) calculate the damaging factors of the radiation accident scenario;
2) to develop a mathematical model for estimating averted damage;
3) compare the costs of preventive measures with prevented damage.

As a research method, a mathematical model of damage assessment is used, which is given in the current “Unified interdepartmental methodology for assessing damage from technogenic, natural and terrorist emergencies, and also classifying and accounting for emergencies” [3]. Some transformations have been made to the method for convenience of calculations.

The object of calculation is a FAPP.

The introduction of an improved methodology and its practical application for the assessment of prevented damage will make it possible to predict the consequences of the occurrence of emergency situations on energy-saturated objects, objects with a massive presence of people. The improved methodology can be used in the EMERCOM of Russia system for forecasting emergencies at the facility level. Also, the topic of this work provides an opportunity for further research in a given direction.

2. Methods

2.1. Initial data
Baseline data for the prediction of radiation contamination: the location of the floating nuclear power plant - the seaport of Pevek; wind direction is mainly northeastern and southeastern, wind speed is 1.3-5.2 m / s; the state of the cloud cover is continuous; the proportion of released radioactive substances is \( \eta = 10\% \). The area of the city is 60.32 km\(^2\). The population density is 67.19 people / km\(^2\), the population is 4053 people [4].

The standard, the specific cost of medical care for one person affected by an emergency during the year \( H1 = 3000 \) rubles. The total duration of the rescue \( TC = 7 \) days; \( t = 8 \) h; The cost of attracting one link in the rescue team for seven days for the subject in question is equal to \( C = 30 \) thousand rubles. The volume of debris \( V = 42000 \) m\(^3\).

2.2. The explosion of oxygen cylinders on board the floating power unit
We used the scenario of a beyond design basis accident in which an explosion of oxygen cylinders occurred as a result of a fire in the CPU, due to an increase in temperature to 450 ° C.

The explosion of gas cylinders on board the semiconductor unit belongs to beyond design basis accidents, since the frequency of implementation is less than 10\(-6 \) events per year (in accordance with NP-064-05. “Accounting for external impacts of natural and man-made origin on objects of atomic energy use”) [5]. Such accidents are not taken into account in the design basis, therefore, in this work, for a more complete analysis of the safety of a floating nuclear power plant, it is required to conduct a predictive damage assessment as a result of such an accident.

Based on a conservative approach, it is assumed that in 30 minutes no measures were taken to evacuate oxygen cylinders. Alert equipment fails at the central control center. Then after 33 minutes, the probability of an explosion becomes maximum.

The following is a calculation of the damaging factors of the explosion.
Excessive pressure in the air shock front, kPa [6]:

\[
\Delta P_\phi = \frac{105}{R} \cdot q_{y.n.}^{1/3} + \frac{410}{R^2} \cdot q_{y.n.}^{2/3} + \frac{1370}{R^3} q_{y.n.},
\]  

(1)

where \( R \) – distance from the epicenter of the explosion, m;
\( q_{y.n.} \) – TNT equivalent in shock wave, kg

For 1 cylinder as in equation (1):

\[
\Delta P_\phi = \frac{105}{7.5} \cdot 0.265^{1/3} + \frac{410}{7.5^2} \cdot 0.265^{2/3} + \frac{1370}{7.5^3} 0.265 = 12.87\text{kPa}.
\]

For 20 cylinders:

\[
q_{y.n.} = 0.5 \cdot 0.53 \cdot 20 = 5.3\text{kg},
\]

\[
\Delta P_\phi = \frac{105}{7.5} \cdot 5.3^{1/3} + \frac{410}{7.5^2} \cdot 5.3^{2/3} + \frac{1370}{7.5^3} 5.3 = 63.83\text{kPa}.
\]

The limiting value of overpressure, which the hull structures withstand, is 50 kPa. The dependence of the excess pressure on the distance to the epicenter of the explosion is shown in Figure 1.

![Figure 1](image-url)

**Figure 1.** The dependence of the excess pressure on the distance to the epicenter of the explosion.

The speed of dispersion of fragments, m/s:

\[
U = a \cdot \bar{U},
\]

(2)

where \( \bar{U} \) - dimensionless reduced speed;
\( a \) – sound velocity in gas at the moment of destruction of the cylinder, m / s.

As in equation (2):

\[ U = 594.22 \cdot 0.95 = 564.5\text{m/s}. \]

The thickness of the equivalent steel barrier, which will not collapse when struck by a flying splinter, mm:
\[ \delta_j = K_c \cdot \sqrt[3]{m \cdot U} \cdot 10^{-2}, \]  

(3)

where \( K_c \) – coefficient depending on the properties of the barrier (for steel \( K_c = 5 \));
\( m \) – fragment mass, kg.

As in equation (3):
\[ \delta_j = 5 \cdot \sqrt[3]{6.7 \cdot 564.5 \cdot 10^{-2}} = 53.3mm. \]

The thickness of the steel lining of the board is 22-30 mm.

As a result of the explosion, fragments pierce the left side and the bottom, radioactive contamination of the terrain occurs.

In the event of a radiation accident, the zone of infection determined by the direction of the wind will extend to the residential sector of Pevek. The sizes of possible zones of radioactive contamination of the terrain on the cloud trail are determined using the method of forecasting the radiation situation during accidents at nuclear power plants [7, 10].

The length of the infection zone was 9 km; width - 0.9 km.

Then the dose rate on the cloud trail:
\[ \check{D} = \check{D}_u \cdot K_t \cdot K_y \cdot K_w, \]  

(4)

where \( K_u \) – coefficient (0.17);
\( K_t \) – coefficient (1);
\( K_w = 10^{-4}nW\xi \)
\( n \) – number of emergency nuclear power reactors;
\( W \) – electric power of a nuclear reactor;
\( \xi \) – the proportion of radioactive substances released from a nuclear power reactor in an accident (10%).
\( K_w = 0.01. \)
\( \check{D} = 0.03 \cdot 1.017 \cdot 0.01 = 0.001 \) rad / h - zone of moderate contamination.

Figure 2 shows the zone of radioactive contamination of the area in the event of a FAPP accident.

Based on the pessimistic scenario, it is assumed that the deadly radiation dose is received by the workers of the floating nuclear power plant - 70 people (\( X_3 \)).

**Figure 2.** The size of the radioactive contamination zone as a result of a radiation accident at FAPP.
2.3. Damage assessment as a result of a FAPES radiation accident

Next, an assessment is made of the projected damage from a radiation accident at FAPP. The assessment is made on the basis of the existing methodology of the Ministry of Emergency Situations with making some changes for convenience of calculation. In particular, new notation indicators were introduced.

Estimation of population losses in the value form $Y_1$ is currently difficult to obtain, so in this case, in the absence of data from the subject of the Russian Federation, it is proposed to estimate this consequence by the number of dead and wounded and not include it in the cost estimate [3].

Evaluation of labor losses:

$$Y_2 = \frac{ПС}{ПУ} \cdot T_5,$$

where $ПС$ – суммарная площадь производственных зданий, получивших свыше второй степени повреждений, m2;

$ПУ$ – total area of industrial buildings that received more than a second degree of damage, m2;

$T_5$ - average expenses for the creation of each new workplace (restoration of previous working conditions) in the subject of the Russian Federation.

Estimation of the cost of providing medical care to the affected population:

$$Y_3 = H_1 \cdot (П - X_3),$$

where $П$ – the size of the affected population (total, irrecoverable, sanitary losses), people;

$X_3$ – irretrievable loss of population, people;

$H_1$ – the norm, the unit cost of medical care per person affected by an emergency during the year, thousand rubles.

An assessment of the damage to industry $Y_4$ is expressed in the cost of rebuilding a floating nuclear power plant.

Estimation of the cost of evacuation and resettlement of the affected population:

$$Y_5 = H_2 \cdot Z_1,$$

where $H_2$ – averaged for the subject of the Russian Federation assessment of the cost of resettlement of one person;

$Z_1$ – the number of settled and evacuees.

Estimation of the cost of providing one-time material assistance to the affected population $Y_6$:

$$Y_6 = H_3 \cdot (X_1 + Z_1),$$

where $H_3$ – averaged per injured rate of payments in case of emergency in the subject of the Russian Federation

$X_1$ – the number affected by the emergency population.

Indicator of costs for rescue operations:

$$Y_7 = ЗС \cdot Ц,$$

where $ЗС$ – the required number of links consisting of seven rescuers simultaneously working in the blockage;

$Ц$ – costs for each link.

Table 1 shows the results of calculations of damage from a radiation accident.
Table 1. The results of the assessment of damage from a radiation accident.

| Name of the indicator                                      | Designation | Units | Value       |
|------------------------------------------------------------|-------------|-------|-------------|
| Labor losses                                               | $Y_2$       | RUB   | 14622015.92 |
| Expenses for medical care                                  | $Y_3$       | RUB   | 1254000     |
| Loss of production fund                                    | $Y_4$       | RUB   | 425723600   |
| The cost of evacuation and resettlement of the affected population | $Y_5$       | RUB   | 4180000     |
| The cost of providing one-time material assistance to the affected population | $Y_6$       | RUB   | 976000000   |
| The cost of rescue                                         | $Y_7$       | RUB   | 3060000     |
| Fines for pollution                                        | $Y_8$       | RUB   | 2700000     |
| Total cumulative damage                                    | Y           | RUB   | 5283349615.92 |

The total damage from the radiation accident at FNPP amounted to about 5 billion rubles.

The calculation showed that as a result of a radiation accident, the cost of damage would not exceed the cost of building a nuclear power plant. However, the possibility of human sacrifice is not excluded. Therefore, when planning the construction of energy-saturated facilities, the design-basis accidents should be considered.

As a preventive measure, it is proposed to move the compartment with oxygen cylinders to a safe distance of 15 m from the side (in accordance with the data in Figure 1). With the explosion of the cylinders in this case, the side of the atomic icebreaker remains intact, only the internal partitions of the deck are destroyed. The damage from the accident in this case is limited to the cost of overhauling the floating nuclear power plant.

In accordance with the Federal Target Risk Reduction Program [8], the level of costs for measures to reduce damage from emergency situations should not exceed 6.43%.

To correlate the level of costs for preventive measures and prevented damage, it is proposed to use the formula of net present value or net present value of an investment project NPV.

The formula includes some transformations in order to adapt to calculations in the field of security in emergency situations [9, 11]:

$$ NPV = -IC + \sum_{n=0}^{N} \frac{CF_n}{(1+r)^n}, $$

where IC – the amount of investments in preventive measures, rub.;
N – the number of periods (years) for which it is necessary to calculate the estimated project;
n – the length of time for which you want to calculate the net present value;
r – discount rate for an innovation project;
$CF_n$ – effect of preventive measures (prevented damage), rub.

3. The experiment
NPV was calculated using Microsoft Excel. NPV is calculated for a period of 12 years, the amount of investment is 6.43% of the damage prevented. The discount rate is 0.47.

The calculation results are presented in table 2.

From the calculations it is clear that the payback period is 3 years. Thus, it can be concluded that investment in preventive measures pays off quite quickly.
4. Results
As a rule, the total economic damage from the impact of various emergency situations on an object is a significant amount. Therefore, it is best to spend some funds on the prevention of consequences to minimize the possible damage from emergency situations.

The effect of preventive measures is significant and exceeds the cost of investments. Therefore, the project will pay off (Figure 3).

![Figure 3. Project payback schedule.](image)

Main results:
1) calculation of damaging factors of the radiation accident scenario;
2) the sizes of zones of radioactive contamination in case of an accident;
3) a mathematical model has been developed for estimating averted damage;
4) the costs of preventive measures are compared with the prevented damage by introducing a new

| Period (years) | Investments (rub.) | The effect of preventive measures (rub.) | Discounted cash flow (rub.) | NPV (rub.) |
|---------------|--------------------|-----------------------------------------|-----------------------------|------------|
| 0             | 339179380          | -339179380                              | -339179380                  | -230 734 272.11 |
| 1             | 440279134.7        | 299509615.4                             | -92 130 164.83              |
| 2             | 440279134.7        | 203748037.7                             | -27 988 322.42              |
| 3             | 440279134.7        | 138604107.6                             | 1 694 607.18 €              |
| 4             | 440279134.7        | 94288508.57                             | 15 430 980.73               |
| 5             | 440279134.7        | 64141842.71                             | 21 787 764.28               |
| 6             | 440279134.7        | 43633906.6                             | 24 729 493.90               |
| 7             | 440279134.7        | 29682929.73                             | 26 090 838.54               |
| 8             | 440279134.7        | 20192469.2                              | 26 720 828.20               |
| 9             | 440279134.7        | 13736373.64                             | 27 012 368.60               |
| 10            | 440279134.7        | 9344471.863                             | 27 147 284.79               |
| 11            | 440279134.7        | 6356783.595                             | 27 209 719.98               |
| 12            | 440279134.7        | 4324342.582                             | 27 238 613.12               |
5. Discussion

The results were discussed and presented at national and international conferences and are part of the methodological bases scientific of risk assessment natural and man-caused emergencies at hazardous technical objects [12].

6. Conclusion

The paper reviewed the scenario for the development of a radiation accident at FAPP. A calculation was made of the impact of the damaging factors of the explosion. The calculation showed that the explosion of oxygen cylinders causes damage to the vessel, and, as a result, radiation contamination of the area. The damage from a radiation accident amounted to 5,283,349,615.92 rubles; therefore, it is necessary to take measures to prevent such consequences. As such measures, it was proposed to move the room with oxygen cylinders to a safe distance from the icebreaker’s side - 15 m.

The calculation of the ratio of the costs of preventive measures to prevent damage has confirmed the need to implement these measures. The payback period for investment in damage prevention was 3 years, which is a good indicator for an innovative project.

Based on the results, it is recommended that preventive measures be taken at all sites to mitigate the consequences of accidents as a result of an emergency. These costs must be considered when calculating the damage prevented. Therefore, appropriate changes should be made to the existing interdepartmental methodology in order to improve the quality of calculation in order to prevent the negative consequences of accidents at the facility level.

The direction of further research is to develop an information and management risk assessment system, which will include a model and methodology for assessing preventable damage.

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