Approach to substantiation of rational decisions on protection of fuel and energy complex objects to the impact of emergency explosions

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Abstract. The article presents in a formalized form the formulation of the problem of finding rational values of the parameters of the basic elements that make up the object of protection and external protection systems of the object (fuel and energy complex) from the impact of an air blast wave. A scientific and methodological apparatus for solving the problem of increasing the security of objects to the impact of an air blast wave in the conditions of restrictions on the parameters of the protection system and resources for the implementation of these measures is formulated. The proposed methodology is based on the security indicator, which makes it possible to interconnect both the intrinsic characteristics of the object and the most probable parameters of the damaging air blast waves. The solution to the optimization problem of delivering the values of the security indicator to the maximum is carried out using the gradient method. The rational parameters of the protection system obtained on the basis of the described approach will make it possible to plan measures to protect the objects of the fuel and energy complex against the impact of emergency explosions in conditions of restrictions on the cost of their implementation.

1. Introduction
At present, despite the measures taken, it is impossible to completely exclude the risk of emergency explosions at fuel and energy complex facilities, this is evidenced in particular by statistics (figure 1) provided in Rostechnadzor reports [1-5].

![Number of emergency explosions](image_url)

**Figure 1.** Statistics of emergency explosions at fuel and energy complex facilities.
Analysis of available methods for assessing the impact of explosive loads on economic objects [6-10] and improving their security [11-14] has shown that measures to increase the security of economic objects to the damaging factors of emergency explosions are based on a number of approaches, including a number of assumptions and restrictions. The measures themselves to protect objects from the effects of emergency explosions are developed and planned in accordance with the plans of engineering and technical measures for civil defense [15].

2. Relevance
The survey and design of building structures of premises, buildings and structures that may be exposed to emergency explosions of gas-steam-dust-air combustible mixtures or explosives is currently carried out in accordance with [14]. At the same time, in the section "Design solutions" of this document, we are talking only about some General recommendations: " for example, when designing explosion-resistant buildings using a frame scheme, the installation of columns along the coordination axes with a step of 2 meters allows increasing the load-bearing capacity of typical wall panels by more than 15 times" [14].

In addition, the approaches described in [14-16] to planning measures to protect fuel and energy complex facilities from accidental explosions do not take into account the contribution of the economic component, despite the fact that the same result can be achieved by performing different measures in different volumes.

In General, the relevance of the problem is determined by the need to develop such tools that would justify the rational choice of parameters of the object protection system, which determines the degree of protection of the entire object from the impact of air shock waves in conditions of restrictions on financial and material resources.

3. Problem statement
Currently, there is a need to determine the list and scope of measures to improve the security of fuel and energy complex facilities aimed at reducing damage from the impact of air shock waves of emergency explosions, but the existing approaches to justify such measures have a number of limitations and disadvantages.

The task is to develop a methodology for selecting and justifying rational parameters of the system of protection of objects of the fuel and energy complex from the damaging effects of air shock waves.

The purpose of this paper is to describe the approach to substantiating recommendations for improving the protection of fuel and energy complex objects from the impact of air shock waves in emergency explosions by selecting rational design parameters of the protection system.

4. Theoretical part
In [17-21], approaches were considered and solutions were proposed to assess the security of construction facilities for various purposes. As an assessment, an approach based on the application of energy methods for assessing the impact of shock-wave load on objects was used. The proposed approach (figure 2) allows for the possibility to influence the value of the security indicator by selecting the characteristics of the security system of an economic object.

The method uses the following parameters as input data:
- information about the location of the object and the conditions of an emergency explosion (Q, R);
- characteristics of the basic elements that make up an object that is the object of shock-wave load (Ψ);
- characteristics of external security systems (Δ)

The restrictions are:
- The maximum (Ψ max) and minimum (Ψ min) values of the base element characteristics to change.
- Maximum (Δ max) and minimum (Δ min) values of the characteristics of external protection systems that can be changed.
Cost of changing a unit of design characteristic $v_\Psi$ and characteristics of protection systems $v_\Delta$

Maximum amount of resources spent on measures to improve the security of the object: $C_{\text{max}}$.

Figure 2. Scheme of methods for increasing the protection of objects to the effects of air shock waves.

The task of searching for rational solutions to protect objects from the effects of emergency explosions is to determine the totality of parameters of structural elements and protection systems, in which the object’s security will be maximum. That is, find such values of the variables $\Psi$ and $\Delta$ that deliver the maximum of the function $k$ (1):

$$k = f\left(<\Psi>,<\Delta>\right) = \frac{\max <\Psi> \max <\Delta>}{\min <\Psi> \max <\Delta>} \to \max,$$

where $<\Psi>$ – found values of the reduced pressure;
$<\Delta>$ - found values of the reduced pulse;
$<\Psi>_{\text{max}}$ is the asymptotic value of the reduced pressure [22];
$<\Delta>_{\text{max}}$ – asymptotic values of the reduced pulse [22].

As values that take into account both the values of the parameters of the air shock wave and the design parameters of the elements that make up the object, $<\Psi>$ and $<\Delta>$ are selected, the formulas for finding which are presented in table 1:

Where $\Psi$ means the following parameters: $x$ - half of the short span of the plate (m); $E$ - young's modulus (Pa); $h$ - total thickness (m); $\sigma_y$ - yield strength, stress (Pa); $p$ - material density (kg/m$^3$); $A$ - cross - sectional area of the beam, column (m$^2$); $b$ - width of the beam (m); $I$ - moment of inertia of the cross - section (m$^4$); $L$ - length of the beam, column (m); $Z$-modulus of plastic resistance (m$^3$); $\Psi_p$, $\Psi_t$,
\( \alpha_p, \alpha_i, \Psi_p, \Psi_i \) - dimensionless coefficients. In turn, the parameters \( \Delta \) are: \( L_{\text{bar}} \) - the thickness of the external protection systems (m); \( \rho_{\text{bar}} \) - the density of the material of the external protection systems (kg/m³); \( R_0 \) is the effective charge radius (reduced to the TNT equivalent) (m) [20].

### Table 1. Models for calculating dimensionless pressure and pulse values [18].

| Element | 2. Dimensionless Pressure | 3. Dimensionless Impulse |
|---------|---------------------------|--------------------------|
| flagstone | \( \{ P \} = \frac{\partial \sigma_y^* h^2}{X^2} * \frac{l_{\text{bar}} * \rho_{\text{bar}}}{P * 60 * R_0} \) | \( \{ i \} = \frac{i \Phi \sigma_y \sqrt{\rho h}}{\sqrt{E}} * \frac{l_{\text{bar}} * \rho_{\text{bar}}}{i * 60 * R_0} \) |
| Pillar | \( \{ P \} = \frac{P \alpha_p E I}{A L^2} * \frac{l_{\text{bar}} * \rho_{\text{bar}}}{P * 60 * R_0} \) | \( \{ i \} = \frac{i \alpha \sigma_y \sqrt{m LI}}{A \sqrt{E} h} * \frac{l_{\text{bar}} * \rho_{\text{bar}}}{i * 60 * R_0} \) |
| Girder | \( \{ P \} = \frac{P \Psi_p \sigma_y Z}{b E^2} * \frac{l_{\text{bar}} * \rho_{\text{bar}}}{P * 60 * R_0} \) | \( \{ i \} = \frac{i \Psi \sigma_y Z \sqrt{\rho A}}{b \sqrt{E} I} * \frac{l_{\text{bar}} * \rho_{\text{bar}}}{i * 60 * R_0} \) |
| Ribbon | \( \{ P \} = \frac{P \Psi \sigma_y Z}{b L \sqrt{E}} * \frac{l_{\text{bar}} * \rho_{\text{bar}}}{P * 60 * R_0} \) | \( \{ i \} = \frac{i A \sigma_y \sqrt{\rho}}{b \sqrt{E} I} * \frac{l_{\text{bar}} * \rho_{\text{bar}}}{i * 60 * R_0} \) |

When solving the optimization problem, you must take into account the restrictions (2) and (3):

- the values of the design parameters to change must not be less than or exceed the allowed values;
- the total resource consumption for all activities must not exceed the specified limits.

\[
\left\{ \begin{array}{l}
\Psi \leq \Psi_{\max}, \\
\Psi \geq \Psi_{\min}, \\
\Delta \leq \Delta_{\max}, \\
\Delta \geq \Delta_{\min}, \\
\sum_{j=0}^{n} C_j \leq C_{\max},
\end{array} \right. \tag{2}
\]

\[
\sum_{j=0}^{n} C_j \leq C_{\max}, \tag{3}
\]

where \( C_j \) is funds spent when changing the \( j \)-th parameter (rubles); \( j \) is the number of parameters of external security systems and basic elements that are changed in the process of increasing the security of the object.

The practical significance, proposals and the results of the implementations, the results of experimental studies.

The solution of the above task is supposed to be carried out by

Let's denote the initial combination of design parameters of basic elements by \( \Psi_0 \{ \Psi_{01}, \Psi_{02} ... \Psi_{0j} \} \), and protection systems by \( \Delta_0 \{ \Delta_{01}, \Delta_{02} ... \Delta_{0k} \} \), the security indicator values will take the form: \( k_0 = f(\Psi_0, \Delta_0) \). i.e., \( k_0 = f(\Psi_{01}, \Psi_{02} ... \Psi_{0j}, \Delta_{01}, \Delta_{02} ... \Delta_{0k}) \) where \( \Psi_{01} \) is the initial value of the 1st structural characteristics \( \Psi_0 \) - the initial value of the \( j \)-th structural characteristics, \( \Delta_0 \) - initial value of the 1st parameter of the system of external protection, \( \Delta_{0k} \) is the initial value of the \( k \)-th parameter of the system of external protection, etc. A valid combination of the design parameters of the base element obtained in s-step optimization let us denote \( \Psi_S \{ \Psi_{S1}, \Psi_{S2} ... \Psi_{Sj} \} \), and the combination of parameters of the external protection systems \( \Delta_S \{ \Delta_{S1}, \Delta_{S2} ... \Delta_{Sk} \} \) respectively the value of the security for the s-step optimization will be equal \( k_S = f(\Psi_{S1}, \Psi_{S2} ... \Psi_{Sj}, \Delta_{S1}, \Delta_{S2} ... \Delta_{Sk}) \).
We consider the problem of maximizing the function \( k = f(\Psi, \Delta) \), provided that the restrictions (2) and (3) are met.

\[
A = \begin{bmatrix}
\Psi_1 & 0 & 0 & 0 & 0 & 0 \\
0 & \Psi_2 & 0 & 0 & 0 & 0 \\
0 & 0 & \Psi_j & 0 & 0 & 0 \\
0 & 0 & \ldots & 0 & \Delta_1 & 0 & \ldots & 0 \\
0 & 0 & 0 & 0 & \Delta_2 & 0 \\
0 & 0 & 0 & 0 & 0 & \Delta_k
\end{bmatrix}
\]

(4)

where \( A \) – matrix of order \( m \times n \) and rank \( m \), the objective function is continuously differentiable in the region definition (items \( A \) – amount of resources needed in appropriate volume measures in the system of constraints, \( m \) is the number of controllable design parameters and parameters of the protection system, which is the maximization, and \( n \) is the number of restrictions). Any \( m \) columns of the matrix \( A \) are linearly independent and each extreme point of the allowed area has \( m \) strictly positive components. Let's take the vector column of maximum and minimum allowed values of restrictions as \( b \). For further convenience, we denote the set \( \{\Psi\} \) and \( \{\Delta\} \) by \( \alpha \).

Stage 1

The transformation of inequalities into equalities is performed by adding additional variables to the left part of the inequalities – residual or redundant (basic variables), which are associated with the inequalities ",\geq" and ",\leq". For inequalities of type ",\leq", a non-negative basis variable (residual) is entered in the left part; for inequalities of type ",\geq", a negative basis variable (redundant) is entered in the left part.

Variables are divided into 2 groups: basic variables \( \alpha B \) and independent variables \( \alpha N \) are selected.

\[
B = \{a_i : l \in I_i\}, \quad N = \{a_i : l \notin I_i\}
\]

(5)

The matrix \( A \) is represented as \([B, N]\), and the vector \( l^T \) is represented as \([l^T_B, l^T_N]\).

A point \( \alpha 1 \) is selected that satisfies the conditions \( A\alpha 1 = b \), \( \alpha > \alpha_{\text{min}} \), \( \alpha < \alpha_{\text{max}} \). (a point with the initial values \( \{X1\} \)).

Put \( s = 1 \) and go to step 2.

Stage 2:

The specified gradient is determined

\[
r^T = \nabla k(\alpha_i)^T - \nabla k(\alpha_i)^T B^{-1} A,
\]

(6)

The possible direction of descent is determined.

\[
d_k = \begin{cases}
-r_i, & \text{if } l \notin I_i, u r_i \leq 0 \\
-\alpha_i r_i, & \text{if } l \notin I_i, u r_i > 0
\end{cases}
\]

(7)

\[
d_B = -B^{-1} N d_{\alpha},
\]

(8)

\[
d^T = (d_B^T, d_{\alpha}^T).
\]

(9)

If \( d_k = 0 \), the search is stopped; \( \alpha_{*} \) is the Kuhn- Tucker point, i.e. the optimal solution is found.

Otherwise, you will proceed to step 3.

Stage 3:

The problem of one-dimensional minimization is solved.
\[
\lambda_{s+1} = \min \left\{ \frac{\alpha_s}{d_s} : d_s < 0 \right\},
\]

where \( \alpha_S, d_S \) are the l-e components of the vectors \( \alpha_S \) and \( d_S \), respectively.

The solution found is \( \alpha^* \{ \alpha^*1, \alpha^*2 \ldots \alpha^*kj \} \) and will be the desired combination of design parameters of basic elements and object protection systems, the implementation of which will increase the object's protection against the impact of air shock waves of emergency explosions.

The next point and the values of the target function at the point are determined:

\[
\alpha^*_{s+1} = \alpha_s - \lambda_{s+1}d_s,
\]

\[
k_{s+1} = f(\alpha^*_{s+1}).
\]

S is replaced with \( s+1 \) and the transition to step 2 is performed. If the condition 2.3 is met, the optimal solution is found.

The results of calculations obtained using the above-described model for searching for rational solutions to protect objects from the effects of air shock waves showed satisfactory convergence with the results of the numerical experiment, as evidenced by the results obtained in [23].

5. Conclusions

The paper presents an approach to finding rational values of parameters of the basic elements that make up the object of protection and external systems for protecting the object from the impact of air shock waves. This approach is based on solving the optimization problem of bringing the values of the object's security index to the maximum. The rational parameters of the protection system obtained on the basis of the described approach will allow planning measures to protect fuel and energy complex facilities against the impact of emergency explosions in conditions of restrictions on the cost of their implementation.

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