

Problematic issues of fire safety in the organization of physical protection of critical infrastructure facilities against military threats

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Complete List of Authors:	Ballo, Yaroslav; Institute of Scientific Research on Civil Protection, Institute of Scientific Research on Civil Protection The State Emergency Service of Ukraine Nizhnyk, Vadym ; Institute of Scientific Research on Civil Protection The State Emergency Service of Ukraine, Institute of Scientific Research on Civil Protection Tverdokhlib, Oleksandr ; Institute of Scientific Research on Civil Protection, Institute of Scientific Research on Civil Protection The State Emergency Service of Ukraine Pozdieiev, Serhii ; Cherkassy Institute of Fire Safety named after Heroes of Chernobyl of National University of Civil Defense of Ukraine Teslenko, Oleksandr ; Institute of Scientific Research on Civil Protection Ballo, Victoria; Kyiv National University of Civil Engineering and Architecture
Keywords:	fire safety, protection of critical infrastructure facilities, fire risks, military threats, evacuation
Abstract:	The article examines fire safety challenges arising from additional physical protection measures at critical infrastructure facilities under modern military threats, drawing on Ukraine's experience. It shows that reinforced concrete shelters and anti-drone systems significantly alter fire safety conditions in existing buildings. Key risks include restricted firefighting access, compromised evacuation routes, reduced ventilation and lighting, and disruption of engineering systems. Using a representative case study, the research analyzes changes in accessibility, evacuation, and formation of enclosed spaces. Numerical modeling of internal explosions reveals that although catastrophic structural failure is unlikely, increased loads may threaten personnel and systems if not considered in design. The study also highlights difficulties integrating ventilation and other systems within protective structures, noting risks such as humidity, corrosion, and degradation. It concludes that protection measures must be combined with a comprehensive, risk-based approach to ensure fire safety, operational reliability, and resilience throughout the facility life cycle.

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8 **Abstract**
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11 measures at critical infrastructure facilities under modern military threats, drawing on Ukraine's
12 experience. It shows that reinforced concrete shelters and anti-drone systems significantly alter fire
13 safety conditions in existing buildings. Key risks include restricted firefighting access,
14 compromised evacuation routes, reduced ventilation and lighting, and disruption of engineering
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16 evacuation, and formation of enclosed spaces. Numerical modeling of internal explosions reveals
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22 life cycle.
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27 evacuation.
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30 **Introduction.** The protection of critical infrastructure facilities is a complex yet
31 critically important task, as it provides the foundation for the sustainable functioning
32 of the state, society, and the economy. Critical infrastructure encompasses vital
33 facilities and systems, including, inter alia, the energy sector, utilities, healthcare, the
34 financial sector, and information and communication technologies. Contemporary
35 military threats, particularly the widespread use of unmanned combat aerial vehicles,
36 necessitate the implementation of additional physical protection measures for various
37 infrastructure facilities or their individual components. Ukraine is among the first
38 countries in the world to have gained real-world practical experience in organizing
39 the physical protection of its own facilities of various functional purposes against
40 aggressive actions by the Russian Federation.
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44 At the same time, the organization of physical protection for buildings and
45 structures often entails a number of associated risks, particularly in the field of fire
46 safety. Additional engineering solutions may lead to catastrophic consequences both
47 for the protected facility itself and for the people who may be present within it. This
48 study presents practical cases in which engineering solutions aimed at enhancing the
49 physical protection of a facility may adversely affect its fire protection systems and
50 create additional risks for personnel.
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55 **Problem Statement.** The active use of combat drones to strike critical
56 infrastructure facilities has become one of the principal threats in contemporary
57 warfare. The low cost of such means of attack, ease of deployment, and, as a
58 consequence, a high rate of successful damage to targets have led to the widespread
59 use of combat drones to inflict harm on facilities of various functional purposes.
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2 Ukraine, virtually immediately after the onset of the full-scale invasion by the
3 Russian Federation, began searching for methods and means to reduce the negative
4 consequences of direct hits by combat drones. In most cases, drone impacts on
5 buildings and structures were accompanied by large-scale fires, resulting both from
6 the detonation of the payload and from residual fuel remaining in the attacking device
7 itself.
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10 Previous studies in the field of protecting critical infrastructure facilities from
11 large-scale fires have predominantly addressed various scenarios of technogenic fires
12 and have focused on issues of prevention, response, and post-incident recovery. In
13 [1], the authors present the results of a study that included a literature review
14 identifying gaps and additional research needs related to the assessment and
15 protection of critical infrastructure, with the aim of enhancing its resilience to
16 extreme fires. However, the impact of physical protection measures on the fire safety
17 regime of facilities was not considered in that work. In [2], a comprehensive analysis
18 of existing approaches to critical infrastructure protection within the European Union
19 is provided, with particular attention to technical and physical security measures;
20 nevertheless, the potential fire-hazardous consequences arising from certain
21 additional engineering solutions are not examined.
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24 Particular attention should be paid to the series of studies [3–5], as they include
25 a high-quality analysis of contemporary potential threats and propose a range of
26 solutions for ensuring effective physical protection of buildings, installations, and
27 technological structures of various scales and functional purposes. At the same time,
28 the effects of changes in structural parameters of buildings and the presence of
29 additional protective structures on the achievement of an adequate level of fire safety
30 remain insufficiently addressed in these works.
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33 It should also be noted that scientific studies devoted to existing methodologies
34 for assessing the security of critical infrastructure facilities [6–8] evaluate potential
35 risks to structures while taking into account their vulnerability and criticality;
36 however, they do not assess the impact of additional engineering solutions on the
37 individual fire risk to the facility and to people present therein.
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40 Accordingly, there arises a need to investigate the impact of additional
41 engineering solutions of physical protection – particularly the installation of external
42 concrete protective barriers and metal anti-drone structures – on compliance with fire
43 safety requirements in the following areas:
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- 46 • restriction of access for fire and rescue units to building façades and roofs, as
47 well as limitations on water supply for external firefighting operations;
- 48 • potential hazards associated with space-planning and structural solutions, as
49 well as the functioning of engineering systems;
- 50 • verification of the preservation of operational parameters of explosion relief
51 structures in explosion-hazardous premises;
- 52 • ensuring the safe evacuation of people from the facility and the increase in
53 calculated evacuation distances from individual rooms to designated safety
54 zones;
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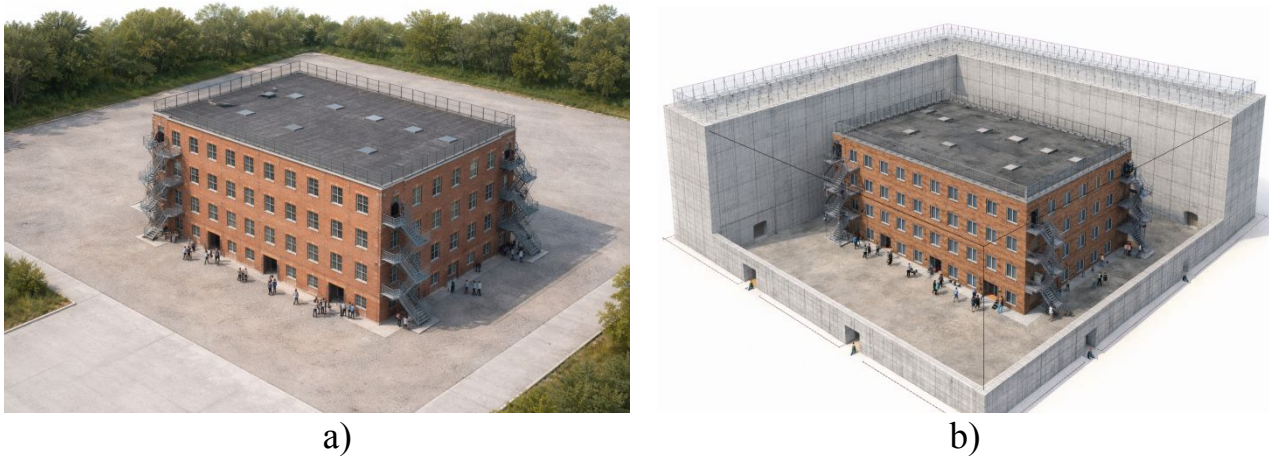
- changes in the intensity of formation of hazardous fire factors both within the internal volume of the building and in the confined space between the building and the protective structure;
- the necessity to integrate existing fire protection systems of the main facility with the fire protection systems of the protective structure.

Based on the above, a comprehensive assessment of the impact of additional engineering solutions on the level of fire safety of a facility is required, with particular consideration given to firefighting accessibility, evacuation of building occupants, operation of engineering systems, and changes in fire risks. The results obtained should provide a substantiated basis for modern technical solutions aimed at integrating protective structures without reducing the overall effectiveness of the building's fire protection systems.

Findings. Let us consider an example of organizing the physical protection of a technical building that constitutes an essential element in ensuring the functioning of a critical infrastructure facility, as well as the potential implications of such protection for the fire safety of the facility. For the purposes of this analysis, the following baseline characteristics of the facility are assumed: a brick-built technical building with three storeys (total notional height of 12 m), a length of 50 m, and a width of 30 m. The floor slabs are made of reinforced concrete and are provided with bituminous waterproofing. The building has windows on each storey, including explosion relief structures for certain explosion-hazardous premises. The building façade is constructed of non-combustible materials.

At least 50 personnel are present in the building during each shift, including night-time operation. From each storey, four distributed evacuation exits are provided via stairwells with natural lighting through windows equipped with transoms; these stairwells lead directly to the exterior at ground level. In addition, two external fire escape ladders are installed, providing access from ground level to each storey and to the roof of the building. The building is equipped with a fire alarm system, a smoke extraction system, and a positive air pressure (pressurization) system for selected premises.

It was decided to provide the building with physical protection comprising two security levels, namely through the use of monolithic reinforced concrete protective structures and metal anti-drone structures installed on the roof. Figure 1 illustrates an example of the described building prior to the implementation of protective measures and after their installation (cross-sectional view).



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Figure 1 – Exterior view of the example study facility, where:
(a) exterior view of the example building without protective measures;
(b) visualization of a cross-sectional view of the protective structure, within which the same building is located.

It should be noted that, despite the conservative nature of the described engineering solutions for forming the physical protection of the facility building and the complexity of their practical implementation, such protective structures are currently widely applied in Ukraine, particularly in the energy sector, to protect critical technological installations. Figure 2 presents a photograph of an implemented example of a similar engineering protection system for a critical infrastructure facility, as well as an image illustrating the condition of the structure after a combat drone strike with an explosive charge of approximately 40 kg [9].

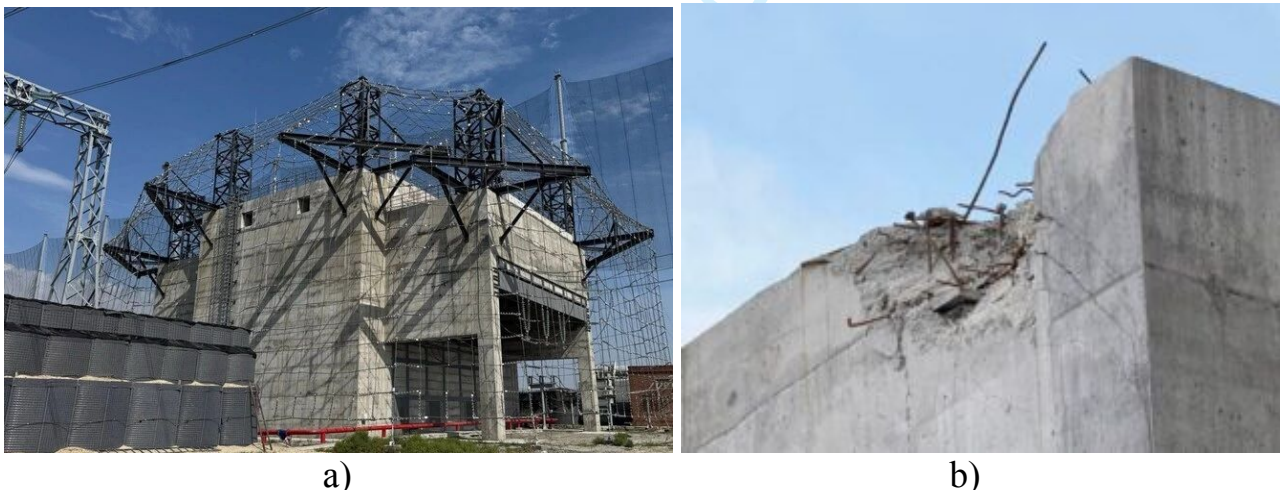


Figure 2 – Example of a typical protective structure for an energy facility:
(a) protective structure with two levels of protection;
(b) consequences of a combat drone impact on the protective structure.

Based on the presented example of engineering protection of the facility and the described space-planning solutions, potential associated fire safety risks that may arise as a result of their practical implementation are considered below.

3.1 Restriction of Access for Fire and Rescue Units

At the initial stage of installing protective structures, it should be taken into account that the original parameters of access roads, driveways, and maneuvering areas will change, as a result of which the access and turning of fire and rescue vehicles may be significantly impeded. In addition, under conditions of existing site development, the installation of projecting structures extending 3–5 m along the perimeter creates an additional risk of restricted access to fire hydrants of the external firefighting water supply system.

The presence of continuous reinforced concrete structures without combustible façade cladding materials, as well as the absence of light openings (windows), eliminates the possibility of façade fire development. However, the risk of fire resulting from technological accidents inside the building protected by the external protective structure remains, which does not eliminate the need for firefighting operations along the façade. In this case, it should be understood that fire and rescue units will be forced to operate within the enclosed space between the protective structure and the building, without natural lighting, while effective access to the roof of the protected building will be absent. Figure 3 illustrates this scenario.



Figure 3 – Visualization of firefighting operations within the space between the protective structure and the facility building

Another problematic issue is the routing of fire hose lines through the doors of the protective structure into the internal space to organize firefighting operations. For such cases, it is advisable at the design stage to provide fixed dry-riser systems to enable connection of fire and rescue vehicles and to reduce the time required for hose deployment through doorways, thermal vestibules, and similar passages [10].

It is also important to recognize that, in the event of a fire within the volume of the protective structure, rapid accumulation of high temperature, steam, and smoke

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2 will occur in an essentially enclosed space. A separate challenge is the provision of
3 lighting within the internal space between the protective structure and the building,
4 including the need to ensure both normal operational and emergency lighting for
5 areas that have lost access to natural lighting.
6

7 Accordingly, key conditions for ensuring effective firefighting operations within
8 the internal space include:
9

- 10 • the prohibition of any combustible materials in the enclosing structures of the
11 protective structure, both on the external façade and roof and on the internal
12 surfaces;
- 13 • execution of roof coverings and waterproofing layers of the building using
14 non-combustible materials, with mandatory removal of existing combustible
15 roofing waterproofing layers;
- 16 • provision of external dry-riser outlets equipped with paired valves at a height
17 of 0.5–1.0 m above driveway level, fitted with hose couplings for connection
18 to mobile firefighting equipment and water supply, in order to ensure the rapid
19 connection of fire hoses and their routing through the exterior enclosing
20 structures of the protective structure; the purpose of each group of dry-riser
21 outlets shall be indicated by appropriate informational signage;
- 22 • provision of unfilled light openings in the external enclosing structures to
23 ensure removal of smoke, heat, and other hazardous fire factors from the
24 internal space between the protective structure and the building; the number
25 and area of such openings shall be sufficient to ensure effective smoke and heat
26 exhaust.
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34 **3.2 Impact of Changes in Space-Planning Solutions**

35 In most industrial buildings and structures, stairwells serving as evacuation
36 routes for personnel utilize natural lighting. This design solution has a number of
37 safety advantages, as it allows acceptable evacuation conditions even in the absence
38 of electrical power supply and enables smoke removal through window openings in
39 the event of fire. It is also an important safety factor for fire and rescue units during
40 firefighting operations.
41

42 However, following the installation of an external protective structure, stairwells
43 with natural lighting completely lose their original safety properties and become
44 hazardous vertical connections between storeys. In the event of a fire, they will
45 rapidly fill with smoke and other hazardous combustion products and will lack
46 illumination in the event of failure of emergency power supply. Figure 4 illustrates
47 this condition.
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Figure 4 – Example of changes in the functional properties of evacuation routes:

- (a) visualization of a stairwell with natural lighting;
- (b) visualization of the loss of natural lighting in the stairwell after installation of the protective structure.

Another critical issue is the increase in evacuation route length and changes in the structural characteristics of certain route segments. Prior to installation of the protective structure, evacuation exits led directly from the building to the outside. Thus, building occupants were able to evacuate quickly to open air via the ground floor in the event of fire. After installation of the protective structure, however, building occupants exiting from the ground floor enter the internal space located between the protective structure and the building. At first glance, an increase in evacuation distance of 5–10 m may not appear critical; however, in the event of a fire within this interstitial space, building occupants may be exposed to smoke and elevated temperatures and may practically become trapped.

Another adverse factor is the change in operational parameters of external fire escape staircases. Whereas prior to installation of the protective structure these staircases had natural lighting and adequate ventilation, after installation they virtually lose their functional purpose, as illustrated in Figure 5.

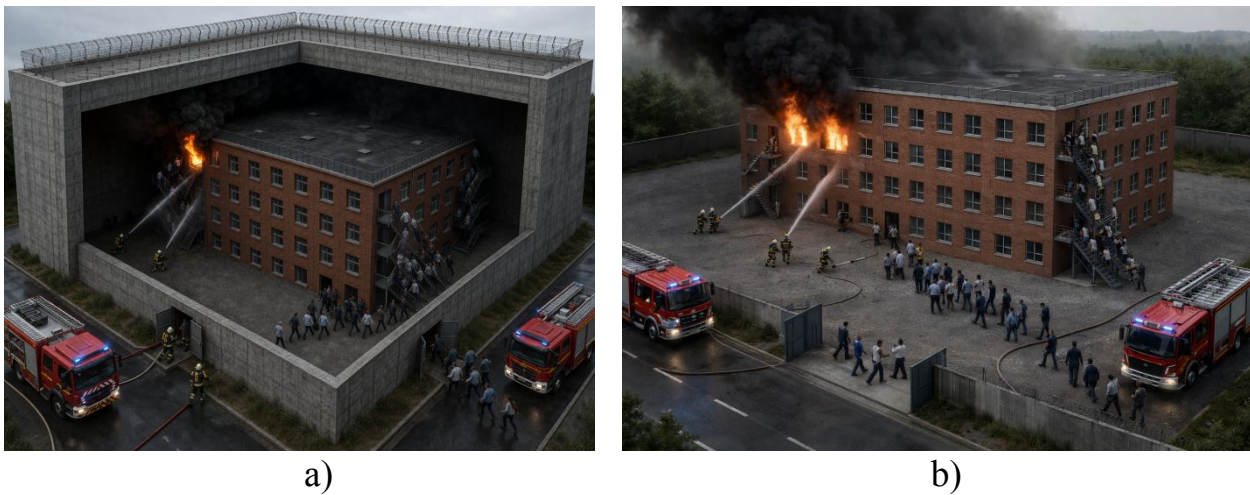


Figure 5 – Example of evacuation via external fire escape staircases in the event of fire:

- (a) evacuation via external fire staircases with direct exit to the outside;
(b) evacuation via fire staircases into the internal space of the protective structure.

Accordingly, essential conditions for ensuring safe evacuation through the internal space of the protective structure include:

- all entrances to the building within the space between the protective structure and the building shall be equipped with fire-rated vestibules and fire doors with a fire resistance rating of at least EI 60, provided with air overpressure during a fire;
- stairwells and fire-rated vestibules shall be equipped with photoluminescent safety guidance systems for use in the absence of emergency lighting;
- external fire escape staircases located outside the building façade shall be separated by fire walls and fire-rated floor structures with a fire resistance rating of at least REI 90, and entrances from each storey as well as roof access points shall be fitted with fire doors rated at least EI 60;
- unfilled light openings shall be provided in the external enclosing structures to ensure smoke and heat exhaust.

3.3 Functioning of Explosion Relief Structures in Explosion-Hazardous Premises

Explosion relief structures play a critically important role in ensuring the safety of explosion-hazardous premises, as they are intended to provide controlled reduction of excess pressure during an explosion. In the event of sudden ignition or explosion of a gas–air mixture, such elements (window infills, panels, roof inserts) fail or open first, directing the explosive energy outward. This significantly reduces loads on the primary load-bearing structures of the building and helps prevent their collapse, thereby reducing the risk of structural failure and injury to building occupants.

In addition, the use of explosion relief structures is an essential requirement of regulatory documents in the field of industrial safety and design. They are

1
2 particularly relevant for facilities involving combustible gases, vapors, or dust, where
3 even slight exceedance of concentration limits may result in an explosion. Proper
4 design and placement of such structures ensure not only personnel protection but also
5 minimization of material losses by localizing accident consequences and facilitating
6 facility recovery following an incident [11–12].
7

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9 From a risk assessment perspective, explosion relief structures constitute an
10 important element of engineering control of explosion and fire hazards, as they
11 reduce the likelihood of catastrophic accident scenarios. Risk analysis considers
12 potential sources of explosive atmospheres, frequency of their occurrence, room
13 volume, and maximum expected overpressure. The presence of explosion relief
14 elements reduces both the probability of total structural failure and the severity of
15 consequences for personnel and equipment, thereby directly affecting the
16 achievement of acceptable risk levels. At the same time, the effectiveness of such
17 structures depends on accurate calculation of their area, placement, and activation
18 conditions; therefore, risk analysis must account for possible failures or delayed
19 activation, which may lead to underestimation of hazards and increased residual risk
20 [13–14].
21

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23 The proposed protective structure has a complex configuration composed of
24 reinforced concrete elements. Its primary objective is to ensure the structural integrity
25 of the enclosing elements of the protective structure during an internal explosion
26 within the interior of a technical building, considering the propagation and reflection
27 of the shock wave and its impact on adjacent premises through openings.
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29
30 To achieve this objective, it is necessary to study the conditions of propagation,
31 reflection, and interaction of the shock wave from an internal explosion on personnel
32 and equipment located in adjacent premises to the explosion source. Under these
33 conditions, experimental investigation of the safety of protective shelters is
34 constrained due to high cost, labor intensity, and elevated hazard. At the same time,
35 modern methods of mathematical modeling have reached a level of development that
36 allows detailed investigation of the physical and mechanical processes occurring in
37 shelter structures during explosions. Therefore, this approach represents a reasonable
38 alternative and may be applied for analogous safety justification calculations.
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40
41 In modeling the explosion, a scenario is assumed in which it occurs in a room on
42 the first floor of the technical building and propagates into the internal space between
43 the building and the protective structure, taking into account reflection of the shock
44 wave. The chemical and gas-dynamic nature of the explosion is not considered;
45 instead, its resultant effects are modeled. The maximum explosion pressure at the
46 shock wave front is conditionally assumed to be 100 kPa. To determine pressure
47 variation on structural walls, the Lagrangian–Eulerian method on arbitrary meshes is
48 applied [15]. Figure 6 presents the computational model of the analyzed building
49 fragment.
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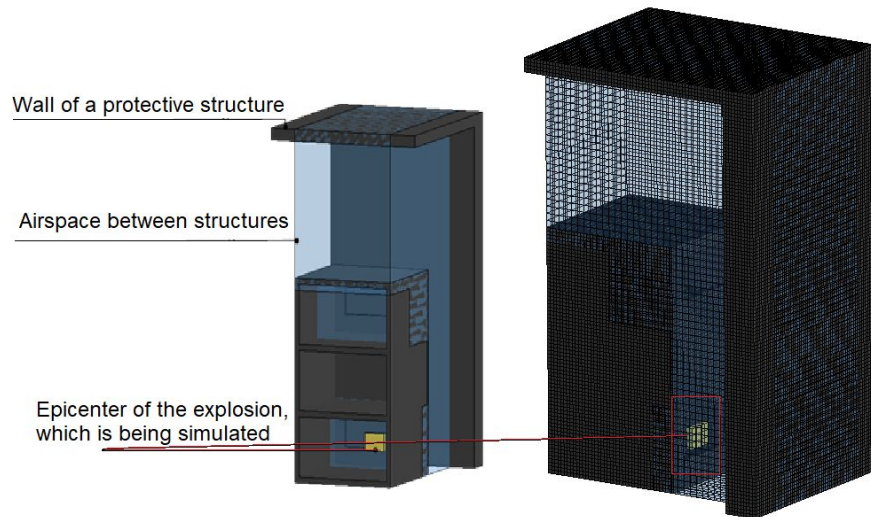


Figure 6 – Simulation model for studying the effects of an explosion

Following the computational analysis, results were obtained that make it possible to investigate the mechanisms of shock wave propagation within the space between the enclosing structures of the protective structure and the building, as well as to assess the potential impact on the enclosing structures of both facilities. Figure 7 presents a map of the distribution of principal stresses in the concrete structural elements (kPa) after application of the explosive load.

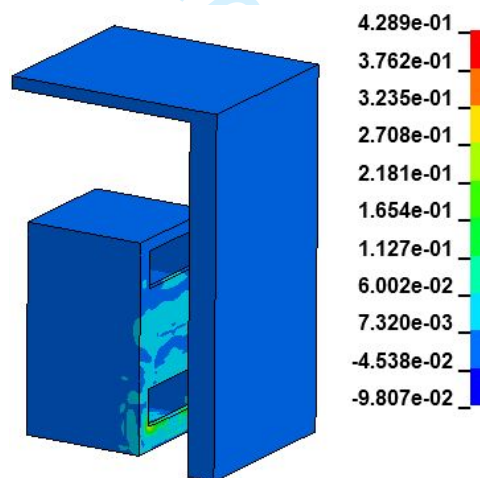


Figure 7 – Visualization of the distribution of principal stresses in the concrete elements of the system as a result of explosion simulation

The propagation of the shock wave front within the investigated structural systems is shown in Figure 8.

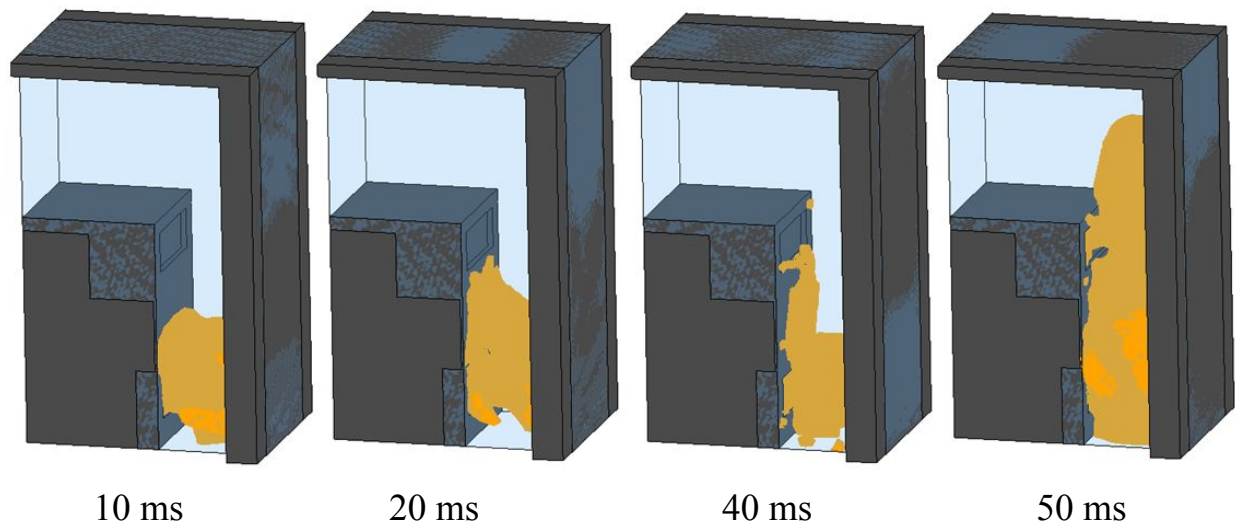


Figure 8 – Visualization of shock wave front propagation in the structural system of the internal space between the protective structure and the technical building at different time moments

Analysis of the simulation results indicates that, for the considered explosion scenario, shock wave propagation within the internal space of the technical building is relatively limited and does not lead to critical destructive consequences for either structure. At the same time, it should be recognized that higher explosive loads may create conditions that could potentially pose a threat both to personnel and to building structures, as well as to their engineering components.

Accordingly, the following conditions are essential to ensure the preservation of the functional effectiveness of explosion relief structures when installing a protective structure:

- conducting a repeated assessment of explosion wave propagation within the internal space between the technical building and the protective structure, taking into account shock wave reflections;
- assessing potential consequences for personnel as well as for fire and rescue units that may be located within the zone of potential impact of the shock wave and fragments of explosion relief structures;
- evaluating the impact of explosive loads on building structures under worst-case design conditions, assuming the realization of maximum intensity and most unfavorable explosion parameters; this assessment should consider peak overpressure of the shock wave, pressure impulse, duration of the compression phase, and the possibility of multiple wave reflections from enclosing surfaces that may generate elevated local loads.

3.4 Integration of Existing Fire Protection Systems.

Engineering systems play a key role in the operation of technical buildings, ensuring their safety, reliability, and operational efficiency. Ventilation and air-conditioning systems maintain appropriate microclimatic conditions for both equipment and personnel, while water supply systems ensure uninterrupted provision of water for technological and sanitary needs. Smoke exhaust systems are a critical

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2 component of fire safety, as they enable rapid removal of combustion products and
3 facilitate evacuation. Lightning protection safeguards buildings and equipment
4 against atmospheric discharges, preventing accidents and damage, whereas power
5 supply systems form the basis for continuous operation of all engineering and
6 technological processes. Collectively, these systems constitute an integrated
7 infrastructure without which stable and safe operation of technical facilities is
8 impossible.
9

10
11 At the same time, a significant proportion of these engineering system
12 components are located on the external enclosing structures of buildings – façades
13 and roofs – due to technical requirements as well as safety and efficiency
14 considerations. In particular, air intake and exhaust devices of general ventilation
15 systems, external units of air-conditioning systems, lightning protection elements and
16 down conductors, components of smoke exhaust systems, and certain elements of
17 power supply systems are typically installed externally. Such placement ensures
18 proper air circulation, heat dissipation, and removal of combustion products,
19 minimizes the impact of hazardous external factors on interior spaces, and facilitates
20 maintenance. However, it also imposes additional requirements on design and
21 installation, particularly with regard to protection against environmental influences,
22 airtightness, architectural integration, and compliance with fire safety regulations
23 during operation.
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26 When installing a protective structure that completely encloses an existing
27 technical building along its perimeter, engineers face the complex task of integrating
28 existing engineering systems into the new structural complex while preserving their
29 functional effectiveness. This requires a comprehensive engineering approach
30 involving reassessment of operating conditions for all systems, taking into account
31 altered aerodynamic, thermal, and operational parameters. In particular, unobstructed
32 air exchange must be ensured through the organization of dedicated channels, shafts,
33 or technical openings for ventilation and smoke exhaust systems, and provision
34 should be made for relocation or duplication of certain equipment elements beyond
35 the protective structure. Engineering solutions must also ensure accessibility for
36 maintenance, repair, and inspection without compromising the integrity of the
37 protective envelope. Special attention should be paid to electromagnetic
38 compatibility, lightning protection effectiveness, and the reliability of power supply
39 systems under conditions of structural shielding. Thus, integration of engineering
40 systems within a protective structure must adhere to principles of redundancy,
41 adaptability, and preservation of the building's design operational characteristics as a
42 whole.
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44
45 Operational experience with such protective structures has demonstrated the
46 importance of ensuring natural ventilation within the internal protective space. High
47 humidity levels and persistent condensation phenomena – where warm, moist air
48 contacts cooler surfaces and water vapor condenses into droplets – are commonly
49 observed. During winter periods, this leads to ice formation on structures and
50 engineering system components, while in warmer seasons it contributes to fungal
51 growth and corrosion of structural elements.
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2 In this regard, the design of protective structures must incorporate solutions for
3 organizing natural or hybrid ventilation of the internal volume to stabilize
4 temperature and humidity conditions. In particular, the installation of ventilation
5 openings or aeration channels that provide continuous air exchange and reduce
6 relative humidity is advisable. At the same time, it should be recognized that an
7 excessive number of openings may adversely affect the quality of physical protection
8 against external threats. Therefore, in certain cases, the implementation of
9 microclimate control systems or periodic forced ventilation may be justified.
10 Ensuring adequate air exchange and humidity control is thus a critical factor for the
11 durability of both the protective structure and associated engineering systems.
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17 **4. Conclusions**

18 The conducted study confirms that the implementation of additional engineering
19 solutions for physical protection – specifically reinforced concrete protective
20 structures and external anti-drone systems – is an effective means of increasing the
21 resilience of critical infrastructure facilities to contemporary military threats. At the
22 same time, such solutions significantly transform the original operating conditions of
23 buildings and structures, potentially giving rise to new hazards, primarily in the field
24 of fire safety. Consequently, ensuring an adequate level of safety is only possible
25 through a comprehensive approach that aligns physical protection requirements with
26 fire safety requirements at all stages of the facility life cycle, from design to
27 operation.
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32 Based on practical experience, it has been demonstrated that the installation of
33 external protective structures substantially complicates access for fire and rescue
34 units to building façades, roofs, and sources of external firefighting water supply. The
35 formation of enclosed or semi-enclosed spaces between the main building and the
36 protective structure alters firefighting conditions, particularly due to the absence of
37 natural lighting, restricted maneuverability of equipment, and increased complexity
38 of hose line deployment. Under such conditions, effective response is achievable only
39 through advance engineering provisions – such as dry-riser systems, dedicated smoke
40 exhaust openings, and lighting – which must be incorporated at the design stage.
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44 The presented examples show that changes in space-planning characteristics of
45 buildings resulting from the installation of protective structures lead to significant
46 deterioration of safe evacuation conditions. In particular, there is a loss of natural
47 lighting in stairwells, an increase in evacuation route lengths, and the formation of
48 internal spaces where smoke, heat, and toxic combustion products may accumulate
49 intensively. This creates additional risks of evacuation route blockage and increases
50 threats to life and health. Accordingly, the implementation of additional fire
51 protection measures is required, including fire-rated vestibules, air pressurization
52 systems, photoluminescent marking, and fire compartmentation of evacuation routes.
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55 The study results indicate that integration of protective structures into existing
56 buildings necessitates mandatory reassessment of engineering system performance
57 (ventilation, smoke exhaust, power supply, lightning protection), taking into account
58 altered aerodynamic and thermal conditions. In addition, it has been established that
59 the presence of an enclosed space between the building and the protective structure
60

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2 affects shock wave propagation characteristics in the event of an explosion and may
3 alter the effectiveness of explosion relief structures. This necessitates the application
4 of advanced mathematical modeling methods to evaluate worst-case loading
5 scenarios and to develop engineering solutions aimed at ensuring structural stability
6 and personnel safety.
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10 11 **Conflict of Interest**

12 The authors declare that they have no conflicts of interest related to this study,
13 including financial, personal, authorship, or other interests that could have influenced
14 the research or the results presented in this article.
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19 This research was conducted without external financial support.
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22 **Data Availability**

23 The manuscript has no associated datasets.
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25

26 **Use of Artificial Intelligence Tools**

27 The authors confirm that artificial intelligence technologies were not used in the
28 preparation of this work.
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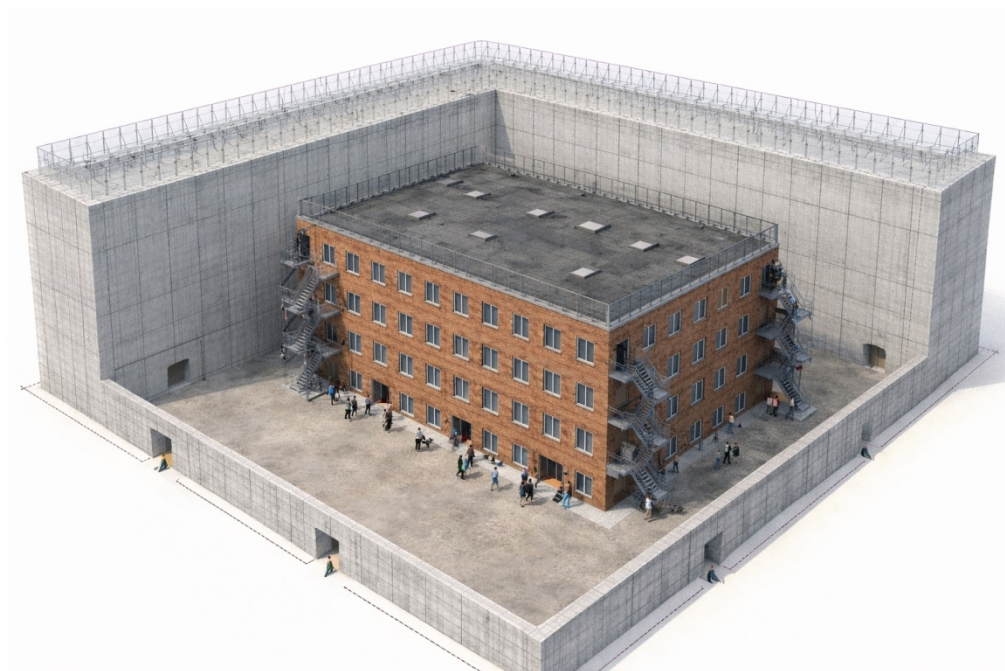
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exterior view of the example building without protective measures

406x270mm (96 x 96 DPI)

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visualization of a cross-sectional view of the protective structure, within which the same building is located.

406x270mm (96 x 96 DPI)



protective structure with two levels of protection

185x122mm (96 x 96 DPI)

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consequences of a combat drone impact on the protective structure

277x194mm (96 x 96 DPI)



3. fire at the facility

403x266mm (96 x 96 DPI)

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4.a. stairs with natural lighting

793x1057mm (96 x 96 DPI)

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4.b. stairs with technical lighting

361x541mm (72 x 72 DPI)

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(a) evacuation via external fire staircases with direct exit to the outside

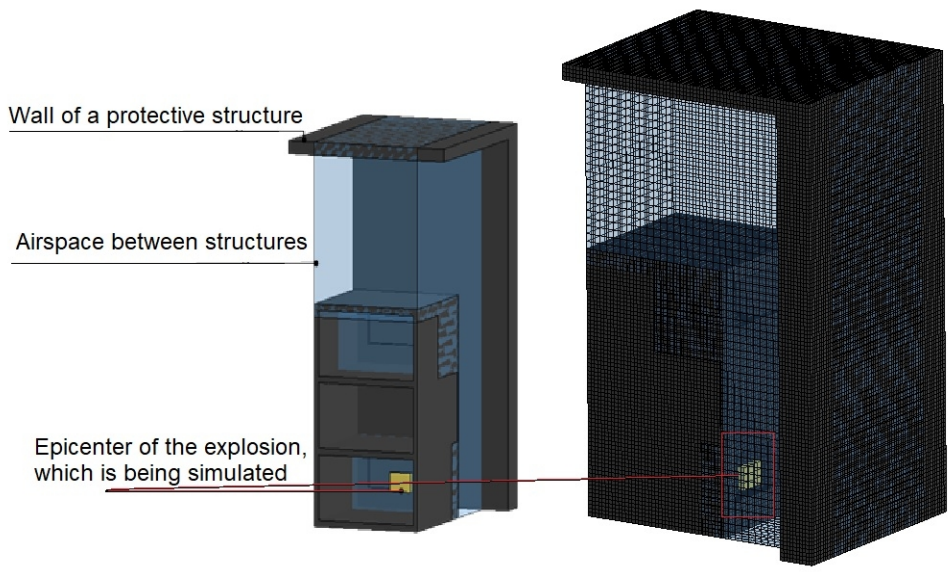
361x270mm (96 x 96 DPI)



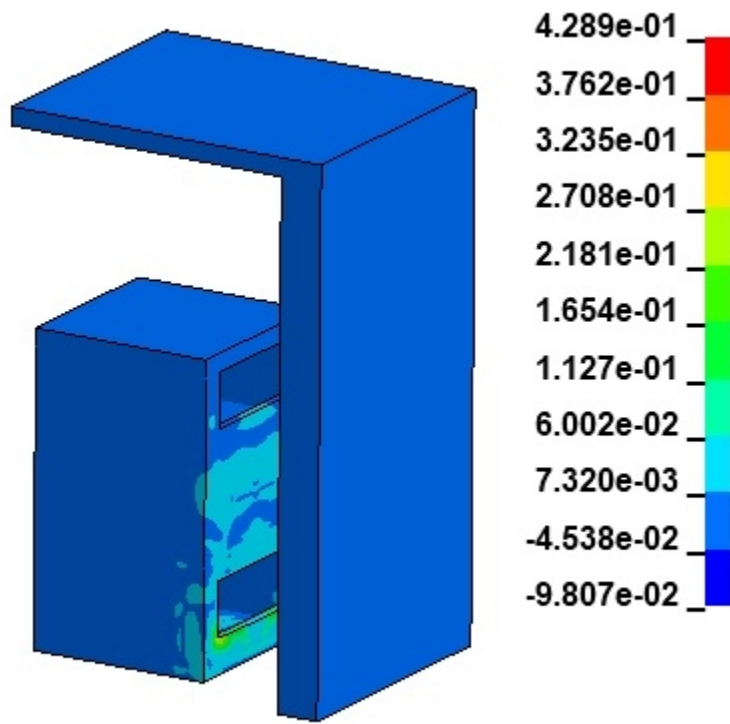
(b) evacuation via fire staircases into the internal space of the protective structure.

406x270mm (96 x 96 DPI)

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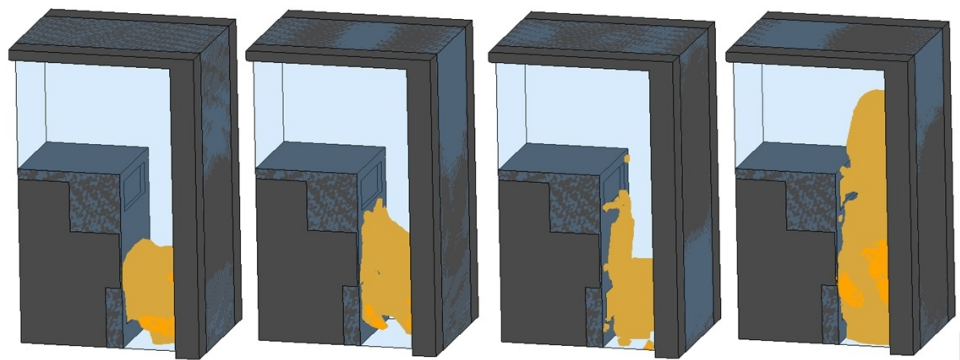
6. Simulation model for studying the effects of an explosion
275x166mm (96 x 96 DPI)



7. Visualization of the distribution of principal stresses in the concrete elements

113x104mm (96 x 96 DPI)

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Visualization of shock wave front propagation in the structural system of the internal space

313x124mm (96 x 96 DPI)