

Collective protection - penetration of contaminated air into facilities

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Abstract

The review article deals with the current issue of collective protection, including collective protection against contamination. The hypothetical threats to the national territory of contamination from toxic industrial agents from high-risk plants (HR) and radioactive materials are presented. Collective protection against toxic industrial agents was characterized, on the basis of NATO documents. The issue of isolation (sealing) of collective protection facilities was discussed. The physical basis of the penetration of hazardous substances into objects as a function of pressure and temperature changes was presented, including ways to protect objects from the penetration of contaminated air.

Keywords: protection against contamination, collective protection, toxic industrial agents, ventilation

1 Introduction

Human activity is associated with increasing environmental exposure. Issues of pollution, waste and by-products of all kinds are now matters of great concern. Paradoxically, in today's industrialized world, the threat of contamination is seen more from local, domestic production facilities or transportation, rather than the possibility of a hypothetical adversary - weapons of mass destruction. The National Headquarters of the State Fire Service, along with the end of each year, publishes a numerical summary of industrial facilities where a major accident could occur due to the amount of hazardous materials stored in them. It is noteworthy that over the past four years the number of facilities classified as posing a high or increased risk has been steadily increasing [1]. The threat may come mainly from a catastrophic chemical release. Given that geopolitically Poland is increasingly linked to Western countries, it also cannot be ruled out that facilities with a large accumulation of toxic materials, including toxic industrial agents - TSP (in the defense standard NO-01-A006: 2010 defines the term TSP - "toxic industrial agents (or TIM - toxic

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industrial material) - radioactive or toxic substances in solid, liquid, gaseous or aerosol form, which can be used or constitute a stockpile necessary for industrial, commercial, medical, military or domestic use. Toxic industrial agents can be chemical, biological and radioactive substances and be described, as toxic biological agents, toxic chemical agents or toxic radioactive agents, and can become a means to carry out terrorist attacks" [2].

At that time, high toxicity ($Lc_{50} < 100 \text{ mg}\cdot\text{min}\cdot\text{m}^{-3}$) and a correspondingly high production level (annual production of 30 or more tons at a single factory) were taken as a measure of the classification of a hazardous chemical into the TIM group. Nowadays, chemicals are classified into the TIM group on the basis of the Hazard Index (HI) value [3]. This criterion is the product of four parameters:

- toxicity (assuming only inhalation poisoning),
- state of aggregation,
- dispersion (number of continents where the substance is produced in quantities of 30 or more tons per year),
- number of producers.

Taking this criterion into account, the UN Economic Commission for Europe has classified some 160 substances as TIMs. Compounds whose HI is greater than 81 were called TIMs with a high index of danger, substances whose $HI \in (36, 80)$ - with a medium one, and those whose $HI < 36$ - with a low index of danger.

TIMs are usually distinguished on the basis of the symptoms of poisoning (toxicological criterion), toxicological classification, and the values of the NDS and inhalation doses.

The hypothetical risk of contamination hazard comes mainly from high-risk (HR) establishments located in the national territory. The number of HR plants, is increasing every year, which increases the risk of a hypothetical accident. Fig. 1 shows the distribution of HRs by province.

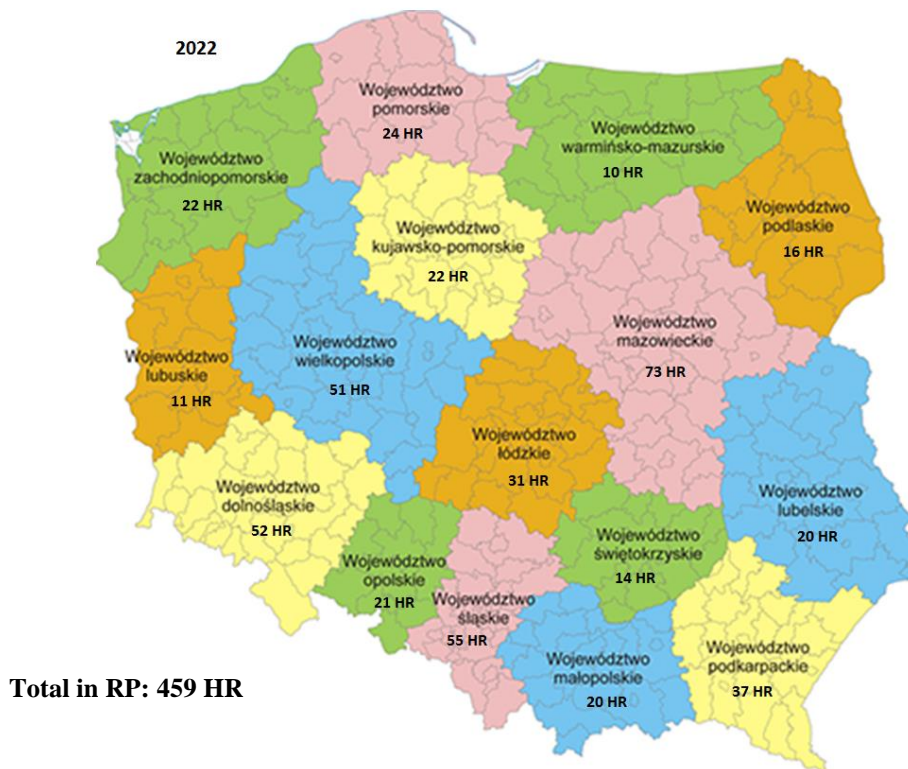


Figure 1: Number of HR category plants in the RP according to the data of the Chief Inspector of Environmental Protection (as of 31.12.2022) [4].

Establishments posing a risk of a major industrial accident are those that meet the criteria set forth in the "Regulation of the Minister of Development of January 29, 2016 on the types and quantities of hazardous substances present at an establishment, determining its classification as an establishment with an increased or high risk of a major industrial accident." The criterion for inclusion of an establishment in the HR register is the production or storage of a listed hazardous substance in a specified quantity. Such substances are defined by hazard categories.

They are divided into division "H" - health hazards, division "P" - physical hazards, division "E" - environmental hazards, and division "O" - other hazards. The categories of substances described above include about 1,600 chemical compounds, but the greatest potential for environmental contamination is held by substances included in the "H" division. This group includes penta and arsenic trioxide, bromine, chlorine, fluorine, formaldehyde, hydrogen chloride, methanol, arsenic hydrogen, anhydrous ammonia, among others. In the country, all major-accident incidents are registered by the Chief Inspectorate of Environmental Protection (GIOŚ) and published as a report at the end of each year. The 2021 report shows that there were 4 victims of industrial accidents, including 3 fatalities. Hundreds of people, mainly plant employees, had to be evacuated during the accidents, material losses were estimated at tens of millions of zlotys [5].

Unfortunately, the terrorist use of TIM and classic chemical weapons by terrorists cannot be ruled out. Chemical weapons are coveted by terrorists because of the scale of their operation and the fact that they are relatively easy to produce. This was clearly highlighted by the actions of the Aum Shinrikyō religious sect, whose most notorious action was an attack using binary chemical weapons. This weapon's chemical composition was most similar to sarin. This action resulted in the death of 12 people and 5500 wounded. We can find information that the sect also produced VX. Synthesized by the sect, it was used in January 1995 to attack three people. Two of them were injured and one died. This person is the first fully documented victim of VX. These incidents underscore the fact that any one of us can become a potential disposer of chemical weapons, and that their use can cause great suffering without any warning [6,7,8].

The first major chemical weapons incident of the Syrian civil war took place on August 21, 2013 in Ghouta. In the early hours of the morning a rocket attack was carried out, sarin was placed in the warheads of the rockets used. About 1,500 people lost their lives, many of them children [9].



Figure 2: *Victims of the chemical attack in Ghouta on August 21, 2013. [10,11].*

On April 7, 2018, airstrikes using chemical weapons took place in Duma, Syria. Initially, it was not known what chemical agents were used in the raid. A report conducted by the Organization for the Prohibition of Chemical Weapons (OPCW) in March 2019 showed the presence of reactive chlorine. A third report dated January 27, 2023, published by the OPCW's Investigation and Identification Team (IIT) found that one of the Syrian Air Force's helicopters dropped one charge each on two residential buildings. The charges did not fully penetrate the buildings but began to release toxic chlorine in high concentrations. It spread rapidly, causing the deaths of some 43 people and adversely affecting the health of dozens of others [12].

The chemical weapons attacks in Syria and Iraq underscore the need to understand the epidemiology of the use of these weapons by non-state actors in particular. According to a review conducted for Disaster Med Public Health Prep, 383 terrorist attacks using chemical weapons were carried out between 1970 and 2017. It is noteworthy that 25% and 12%, respectively, of the targets of such attacks were private individuals and educational institutions. The statistical number of attacks increased on average from 6 per year between 1970 and 2011 all the way up to 24.9 for 2011-2017 (this period coincides with the conflict in Syria) [13].

Chemical weapons, one of the weapons of mass destruction, have always posed, and presumably will continue to pose, a threat to any facility for a long time to come. Therefore, it is impossible not to take it into account when

assessing potential threats. Its primary advantages are its ease of access (it can be synthesized in laboratory conditions) and its immediate effect. The main factors determining its applicability are:

- ability to penetrate inside objects if they are not airtight;
- minimal damage to material things;
- large gross effects with little effort on the part of the attacker.

It is widely estimated that in the current political and military situation, Poland may be at risk of being hit by nuclear weapons. However, as long as there is a real possibility of producing or purchasing fissile materials (uranium, plutonium) and finished nuclear warheads the threat is high and real. It is well known that the countries of the former Soviet Union belong to the group of countries with a very low level of security and protection of facilities possessing fissile materials: reactors, power plants, nuclear fuel reprocessing plants, radioactive waste repositories and, above all, nuclear weapons storage facilities, of which there are about 400 tons. The failure to ensure security is evidenced by the reported high number of thefts of various types of radioactive materials, mainly plutonium and uranium. It is worth mentioning that 375 radioactive sources (including devices using radioactive sources) went missing or were stolen in Russia in 2000 - this gives one incident per day. The primary factor in assessing the threat of using nuclear weapons is the type of fissile material available and its quantity. In the case of terrorist groups, obtaining any radioactive substance may be a problem.

In terrorist plans found by U.S. special forces in Afghanistan, designs were found for an attack using precisely the dirty bomb. It is simple in design, and the radioactive material can come from radioactive waste sites that are not the best protected. Given the determination of members of terrorist organizations, they would not hesitate to sacrifice their own health and lives to extract the waste and reprocess it so that it spreads well in the atmosphere. A serious risk is the availability of plutonium in commercial MOX (Mixed Oxide - a mixture of uranium dioxide and plutonium) fuel reprocessing plants. To date, more than a hundred tons of plutonium have been separated in this way - an amount that could soon exceed the world's production of military plutonium. This material is stored in many countries, not all of which adequately secure it. Today's global threat is not only Russian nuclear weapons located in launch pads throughout Russia - poorly protected and inadequately secured against uncontrolled firing, but also technically inoperative.

The worrisome situation in Ukraine today is unstable, and it is unclear how long the power plants will be in Ukrainian hands - Fig. 3. Given that the RP is within the range of radioactive aerosols that would result from nuclear reactor accidents.

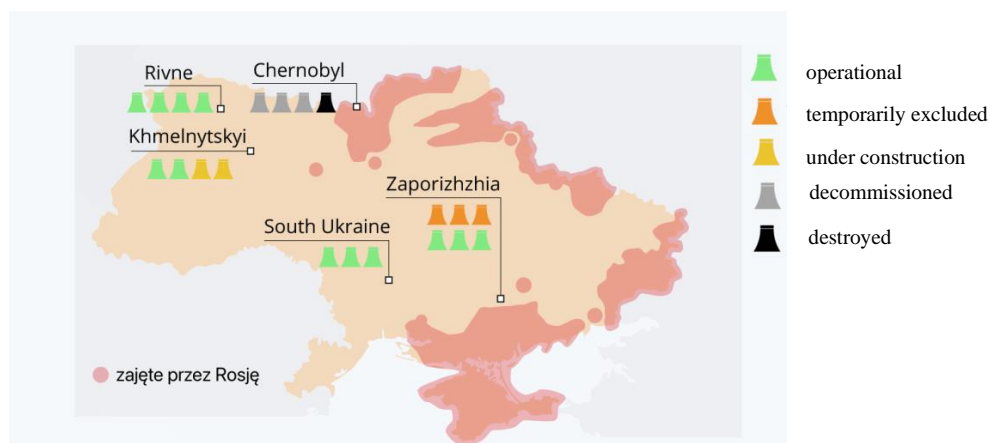


Figure 3: Location and status of nuclear power plants in Ukraine [14].

After the events at Chernobyl, when radioactive aerosol contamination covered almost all of Europe, all nuclear power plants in the vicinity of RP should be treated as a potential threat.

Suggestions that Russia might use nuclear weapons have been around since the beginning of the Russian invasion of Ukraine. The first were made back in 2014, after the annexation of Crimea. In February of that year, Vladimir Putin announced a strong response if the West became involved in the conflict. Russia even suggested "escalation" in response to arms supplies to Ukraine. Is this just cynicism designed to intimidate the international community? Also in February this year, Russia is withdrawing from the New START treaty, which, on Russia's part, has not been

complied with, as the U.S. State Department states that the U.S. has not been able to inspect Russia's nuclear arsenal for at least three years.

Following the conflict in Ukraine, it can be concluded that mostly missile and drone attacks are directed at civilian facilities, including residential infrastructure, schools, hospitals, etc.

2 Collective protection against toxic industrial agents

Because of the widespread use of toxic industrial agents, NATO attaches great importance to ensuring adequate protection against them. The probability of threats involving toxic chemical agents is much higher than the use of CWA, since most countries that have renounced the possession and use of chemical warfare agents by ratifying the Chemical Weapons Convention have sufficiently developed chemical industries [15]. Unlike CWA, many TIMs have flammable and explosive properties. Although fires and explosions tend to have local effects, one should be aware of additional hazards. There is a particular explosion hazard in the vicinity of pressurized installations with liquefied flammable gases. Of additional importance is the fact that protective equipment in the armed forces provides limited protection against TIM. ATP Publication 3.8.1. in the chapter on recognition of TIM contamination notes that personal protective equipment provides protection against ingestion of radioactive aerosols by ingestion and inhalation, but does not provide protection against gamma radiation. When it is necessary to carry out activities (other than evacuation) in a radiologically contaminated area, it is recommended to use expert assessment of whether standard PPE provides adequate protection [16].

In addition to the threat of combat assets, threat assessments during the planning and conduct of operations should also take into account threats that may be posed by industrial assets. Guidance on TIM threat levels and corresponding protection measures recommended for NATO forces was contained in the withdrawn Stanag 2516 [17]. The following TIM threat levels were established (Table 1).

Table 1: Hazard levels for toxic industrial agents
(Source: STANAG 2516, Annex A, Table 1).

Level	Description of the threat
Zero	TIMs do not occur in the area of combined operations (ODP)
Very low	TIMs are present in the ODP, but are in secure installations. There are no indications of deterioration of safety.
Low	Risk of TIM release very low or no risk at present. There are indications of the possibility of deterioration of plant security.
Medium	Hostilities are likely or underway. The risk of TIM release is increased due to progressive deterioration of security and destruction of installations. TSP release may occur after additional warning.
High	The situation has escalated into open warfare. Damage to industrial security systems is widespread. TIM releases have occurred in the ODP. There is a risk of further TIM releases without warning.
Very high	There is a risk of a TIM release in the immediate area without warning. There may be indications that enemy forces intend to cause a TIM release in a specific area.
Occurrence	A release of TIM has occurred in the specified area.

According to the established level of danger, STANAG 2516 recommends, at a minimum, the use of personal and collective protective equipment in accordance with Table 2. As a general rule, the use of measures that provide a degree of protection appropriate to the existing threat. Commanders have the authority to increase or decrease the degree of protection in a specific area, depending on the local situation.

Table 2: Recommended protection measures depending on the threat level of the TIM
(Source: STANAG 2516, Annex A, Table 2).

Level	Individual protection		Collective protection		Procedures
	respiratory protection	skin protectors	personnel	equipment	
Zero	available ¹	available	available	available	no
Very low	arranged ²	arranged	available	available	no
Low	issued ³	gotowe ⁴	arranged	arranged	planned
Medium	issued	issued	ready	ready	tested
High	issued	issued	spaced	spaced	tested
Very high	issued	issued	operational	used as needed	used
Occurrence	used as needed	used as needed	occupied	used as needed	used

¹ available - in the national supply chain,

² deployed - delivered to the area of combined operations,

³ issued - issued to soldiers,

⁴ ready - stored in the subdivision or by soldiers, as decided by the commander.

More detailed guidance on protection against toxic chemicals is provided in STANAG 2909 [15]. The risk posed by TSPs arises from their use in production, storage and transportation in large quantities. Among the prerequisites considered when assessing the threat posed by chemicals under specific environmental conditions are sufficiency, volatility, toxicity, flammability and corrosive properties (STANAG edition 2 [18], which is in the process of being ratified, adds reactivity and causticity to the listed characteristics).

In most cases, the main hazard is TIM vapors (inhalation hazard). Near the release site, the concentration of the agent's vapors can be very high. Although typical military filtering devices provide some level of protection against most TSPs (depending on the concentration, time of exposure, form of occurrence) however, an adequate level of protection cannot be guaranteed. Therefore, immediate evacuation from the hazardous area is recommended. Typical filter canisters can be used during evacuation. In addition, TIMs in high concentrations can displace oxygen from the air, rendering gas masks completely ineffective. If the toxic cloud has a higher density than air it moves to lower-lying areas (valleys, ravines). It can linger in the basements of buildings, forests and other places with reduced air circulation. Therefore, commanders and emergency management organizers should be aware of the capabilities and limitations of TIM protection measures relative to industrial chemicals.

Edition 2 of STANAG 2909 gives the approximate effectiveness of military filters against 98 chemicals:

1. effective (for 34 substances) - the filter absorber should reduce the hazard to an acceptable level for a time sufficient to evacuate the hazardous area. This does not mean that personnel in the hazardous area are not at risk. The degree of effectiveness of a filter absorber depends on the concentration, exposure time, weather conditions and its initial condition. Marginal (for 33 substances) - filter absorbers do not reduce the hazard to an acceptable level for a long enough time, sufficient to evacuate the from the contaminated area, but provide protection during the initial period.
2. weak (for 31 substances) - the filter absorber does not reduce the hazard to an acceptable level, but provides protection in the initial period for a short time (less than 5 minutes) depending on the concentration and other conditions.

The cited data is based on the Edgewood Chemical Biological Center US ECBC-TR-093 report "TIC assesment on NBC Filter performance" and refers to the filter absorbers in the equipment of the US forces[19]¹). It is recommended to verify the given recommendations for the standard filter absorbers used.

It should be remembered that military WMD protection measures in most cases do not provide effective protection against TIM. In addition, the armed forces lack equipment for detection, identification and elimination of TIM contamination, which poses additional challenges for commanders.

¹ FM Instruction 3-11.4 contains a table with the evaluation of the effectiveness of the military's TIMs against the same substances. In addition, TIMs are divided into three groups depending on the hazard posed.

3 Insulation (sealing) of objects [19]

It is known that in residential homes, public buildings and others, air from the surrounding atmosphere freely penetrates into the interior. Also, air from the interior of buildings easily penetrates to the outside. The reason for this natural exchange of outdoor and indoor air of ordinary buildings is the very construction of the buildings themselves and the properties of the materials used. These structures have, openings, gaps in doors and windows, walls, ceilings, etc. In addition, the materials used in their construction are porous and easily let air through. To induce air movement from one side of the partition to the other, there must be a pressure difference on both sides.

Also, under conditions where poisonous, radioactive or biological agents are used, there will be penetration of external contaminated air into buildings. The term penetration of contaminated air refers to enclosed spaces where people do not enter (exit). Buildings, characterized by high air permeability, cannot be used for collective protection, because both contaminated air and shock wave can penetrate.

To achieve proper airtightness of buildings, intended for collective protection, it is necessary to isolate them as completely as possible from the outside atmosphere. However, it is practically impossible to ensure the complete airtightness of buildings, since even if they are very carefully sealed, there always remain small gaps between individual structural elements and pores in building materials. Therefore, some air permeability is inevitable, and this is true even in specially sealed and protected objects.

The penetration of contaminated air into closed and sealed rooms occurs over time. After a certain period of time, an unacceptable concentration of toxic substances may form inside the premises and under certain conditions, and then the operation of such premises without the use of personal protective equipment may be impossible.

Therefore, the degree of insulation of the premises should protect against the penetration of minimally permissible amounts of contaminated air within a certain period of time. In order to determine the necessary degree of containment of shelter rooms, it is necessary to consider the causes causing penetration and the process of penetration of outside air into the interior of the collective protection facility itself.

4 Causes of penetration of contaminated air into facilities [20]

Quantitatively, the penetration of contaminated air can be defined as the volume per unit time V [m³/h] that passes through a given structural element (doors, vestibules, partitions, etc.) or through 1 m^2 of partition surface (walls, ceiling) at a given pressure difference.

In the most general terms, the amount of penetrating contaminated air depends on two factors:

- the pressure difference Δp of the air on both sides of the partition;
- the size and shape of holes, gaps and pores.

For a given structure, the amount of contaminated air penetrating is a function of the pressure difference:

$$V = f(\Delta p) \quad (1)$$

The difference in pressure Δp on both sides of the partition can arise from the following causes:

- wind action on the structure;
- the difference in air temperature inside and outside the room;
- the shock wave pressure of a nuclear explosion or conventional charge;
- the pressure prevailing inside the room.

If there is no pressure difference on either side of the partitioning element ($\Delta p = 0$), the penetration of air into the interior is possible only due to the phenomenon of diffusion, which is usually not taken into account because of its low practical significance.

The amount of wind pressure on the surface of the partition can be approximated by the formula:

$$\Delta p_w = A \frac{\gamma \cdot v_w^2}{2g} \cos \alpha \quad [\text{Pa}] \quad (2)$$

where:

v - wind speed in m/s;

g - acceleration of the earth – 9,81 in m/s²;

γ - specific gravity of air in N/m³;

A - aerodynamic coefficient depending on the shape of the partition;

α - angle between the perpendicular of the baffle surface and the wind direction.

For $\cos \alpha = 1$, the wind pressure is greatest and equals:

$$\Delta p_{w\max} = A \frac{\gamma \cdot v_w^2}{2g} \quad (3)$$

The magnitude of A for the windward side of the object takes a positive value (from 0 to 1), for the leeward side a negative value.

In the general case, the pressure difference, resulting from the action of wind on the object Δp_w is expressed by the formula, taking into account the pressures on the windward side

and leeward sides:

$$\Delta p_w = A_1 \frac{\gamma \cdot v_w^2}{2g} - A_2 \frac{\gamma \cdot v_w^2}{2g} = (A_1 - A_2) \frac{\gamma \cdot v_w^2}{2g} \quad (4)$$

The average values of aerodynamic coefficients are:

- for the windward side $A_1 = +(0,7 \div 0,8)$;
- for the leeward side $A_2 = - (0,15 \div 0,20)$ [20].

The effect of wind pressure is taken into account only for objects having walls (or parts of walls) projecting above the ground surface. In the case of object movement with speed v_r , instead of wind speed v_w , the sum of wind speed v_w and object speed v_r is substituted into the formula, obtaining:

$$\Delta p_{\max} = (A_1 - A_2) \frac{\gamma}{2g} (v_w + v_r)^2 \quad (5)$$

The pressure created by the temperature difference can be determined from the formula:

$$\Delta p_t = H(\gamma_z - \gamma_w) \quad (6)$$

where:

H - the distance between the centers of the openings through which air enters and leaves the room to the outside in m;

γ_z and γ_w - specific weights of external and internal air in N/m³.

The greatest pressure difference can occur in winter conditions, when the temperature difference between outdoor and indoor air is at its maximum. In order to quantitatively assess the value of the pressure difference in each case, it is necessary to consider the schematic diagram of a specific facility with entrances, shafts, etc. marked on it, and calculate Δp_t according to the above formula for different operating conditions of interest.

For underground facilities, schematically shown in Fig. 4, under winter conditions ($t_z = -20^\circ\text{C}$ and $t_w = +25^\circ\text{C}$), the value of Δp_t will be::

- for a facility with horizontal and shaft entrances (fig. 4a):

$$\Delta p_t = 30(1,4 - 1,19) = 6,3 \text{ [mm. sł. } H_2O = 61,80 \text{ [Pa]}]$$

- for a facility with two shaft entrances (fig. 4 b):

$$\Delta p_t = 10(1,4 - 1,19) = 2,1 \text{ [mm. sł. } H_2O = 20,60 \text{ [Pa]}]$$

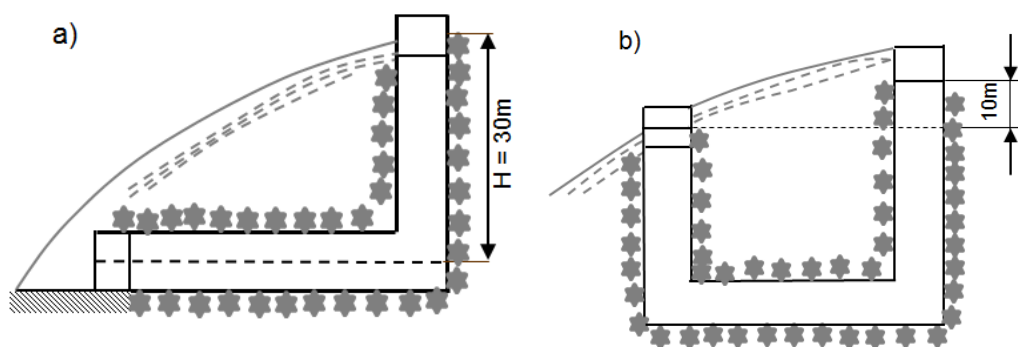


Fig. 4. Schemes of underground facilities:

a/ with a horizontal and shaft entrance; b/ with shaft entrances [20].

With the presence of gaps in the entrances, contaminated air will penetrate into the facility in winter conditions through openings located below, warm air from inside the facility will go out through openings located above.

With vertical entrances located at the same level, the movement of cold and warm air in winter conditions can take place in the same shaft, with warm air passing through one side of the shaft and cold air through the other side (when the distance between shafts is large).

In summer conditions, the value of Δp_t will be lower than in winter. So, for example, for the first object (Fig. 4 a) at $t_z = +35^\circ\text{C}$ and $t_w = +15^\circ\text{C}$.

$$\Delta p_t = 30(1,146 - 1,226) = -2,4 \text{ [mm.sł. } H_2O] = -23,54 \text{ [Pa]}$$

The "minus" sign indicates that the direction of air flow will be opposite to that in winter conditions. When $t_z = t_w$, the pressure difference will not occur ($\Delta p_t = 0$), and air penetration takes place only due to the process of diffusion and the action of wind on the inputs.

The examples cited for the theoretical determination of Δp_t referred to facilities with open entrances. In practice, facilities are equipped with airtight closures and separated vestibules, in which there is a temperature difference. Therefore, outside air in winter cannot penetrate in large quantities into the facility. Air penetrates in small quantities into the facility through all kinds of leaks due to the temperature difference in the lower in the upper part of the room (Fig. 5).

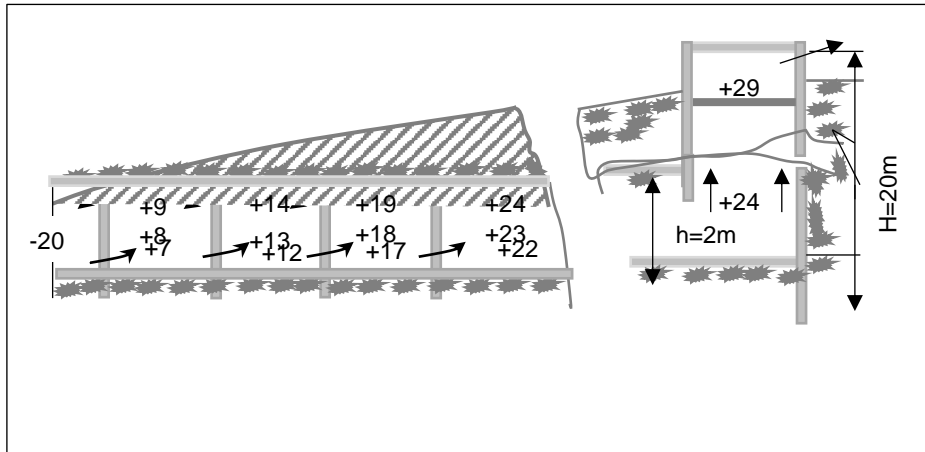


Fig. 5. Diagram of temperature distribution in an underground facility [20].

The shock wave pressure of a nuclear explosion Δp_f can play a significant role in all types of objects, because regardless of the short duration of its action (from tenths to a few seconds), its magnitude, even at considerable distances from the point of explosion, is very large (up to hundreds of thousands of Pa).

As a result of the pressure of the shock wave, significant amounts of outside air can be forced into the interior of objects through all kinds of leaks and uncontaminated soil. If the surrounding area is contaminated with poisonous, radioactive or biological agents, contaminated air enters the facility.

The penetration of contaminated air depends not only on the magnitude of the pressure difference Δp on both sides of the partition, but also on the size and shape of holes, gaps, etc.

In practice, the size and shape of holes, gaps and pores, also the total number of them can vary. Therefore, taking these parameters into account in theoretical calculations is practically impossible. Even in the same object, the size and shape of gaps and holes can change during operation due to a number of causes (stresses, shocks, etc.).

For a rough estimate of the amount of air penetrating through all kinds of leaks, it is expedient to divide these leaks into three groups:

- large holes;
- cracks and small holes;
- porous structural elements.

In the case of air penetration through large openings (open entrances, firing ranges, ventilation ducts, etc.), which can be considered as venturis or diaphragms in the path of the flow of a wide air stream, the amount of air penetrated per unit time at a small pressure difference (up to 1000 Pa) can be approximately determined from the product of the air velocity and the cross-sectional area of the opening:

$$V = S \cdot v \quad (7)$$

Then substituting v from the formula for Δp_{wmax} (3) and taking into account the flow coefficient we get:

$$v = \mu S \sqrt{\frac{2g}{\gamma} \Delta p} \quad (7a)$$

where:

V - amount of air permeating in m^3/s ;

S - total cross-sectional area of openings in m²;

Δp - pressure difference on both sides of the opening in Pa;

γ - specific gravity of air in N/m³;

g - gravitational acceleration – 9,81 m/s²;

μ - flow coefficient, generally μ < 1, for diaphragms with sharp edges μ = 0,6.

Air penetration through gaps and small openings has a more complex character. They can be considered as narrow channels of various lengths and shapes. In these channels there are constrictions and kinks, which create local resistance to the flowing air stream, the phenomenon of internal friction occurs, and turbulence of the air stream is possible. In this case, the relationship can be applied:

$$V = \alpha \sqrt{\Delta p} + \beta \Delta p \quad (8)$$

where:

α and β stand for coefficients that characterize the shape and dimensions of leaks, with α depending on the air density ρ, while β depends on the air viscosity η.

The values of α and β coefficients for given conditions can be found experimentally.

The passage of air through porous materials or leaky structural elements of objects under the influence of differential pressure is similar to the viscous flow of air through capillaries. In this case, to determine the amount of air, passing through porous materials at time t with sufficient accuracy can be used the relationship:

$$V = B \frac{F}{l} \Delta p \quad (9)$$

where B is the coefficient of air permeability through a given material

$$B=V; \text{ m}^3/\text{h at } F = 1 \text{ m}^2; l = 1 \text{ m}; \Delta p = 1\text{N/m}^2 (9,81 \text{ Pa})$$

where:

Δp - pressure difference on both sides of the porous partition in N/m²(Pa);

F - area of the structure or material in m²;

l - material thickness in m.

Table 3 lists the B values for various materials at F = 1 m², l = 1 m, Δp = 1N/m² (9,81 Pa) [20].

Table 3: Values of air permeability coefficient B for various materials

Material	B w m ³ /h
Sand (moisture content of 3,5%)	
- slaughtered	0,05 - 0,1
- unslaughtered	0,2 - 0,9
Clay + sand (1:1) - moisture content 14 %	
- slaughtered	0,01
- unslaughtered	0,1 - 0,6

Concrete	$2,5 \cdot 10^{-4}$
Brick	$2,0 \cdot 10^{-4}$
Oil paint	$1,0 \cdot 10^{-5}$

As can be seen, air permeation through concrete partitions is negligible with sufficient partition thickness. Painting the surface of the partition with oil paint significantly reduces the air permeation through the partition. However, with a large pressure difference and large areas of the partition, air permeation can be significant.

4.1 Processes of penetration of contaminated air into a closed facility [20]

Experience and theoretical calculations show that due to the penetration of contaminated air into the facility, caused by the difference in pressure, a dangerous (toxic) concentration of poisonous, radioactive and biological agents can form inside the premises over time. If at the same time the room is not ventilated, the concentration inside the facility can reach a value equal to the external concentration.

In order to determine the time to reach the toxic concentration and the minimum permissible concentration, the process of penetration of contaminated air into unventilated or ventilated rooms where the filtering system is not in operation should be further considered.

The process of penetration of contaminated air into the facility through various types of leaks can be schematically presented as follows.

Under the action of pressure difference Δp external contaminated air penetrates into the facility through various leaks and mixes relatively quickly. This process, however, should not be regarded as forcing outside air into the airtight room, because as a result of the slight overpressure inside the room, some air exits the room through other leaks. With this, the volume of air entering at any given time equals the volume of air leaving.

In order to express this process mathematically, we assume that mixing of the air entering the room with the indoor air occurs immediately and that the room air was clean to begin with, and that sorption of the harmful substance on the surface of structural materials does not occur. Let v in m^3/min of external contaminated air enter the room with a volume W in m^3 at time t , with a constant external concentration of the toxicant, radioactive substances and biological aerosols of C_0 in g/m^3 , by time t in the room, a concentration of C in g/m^3 will be established due to the infiltration of external air.

Then, in the time dt , the amount of harmful substance will penetrate into the interior $dm_1 = C_0 \cdot v \cdot dt$. During the same time, the following amount of harmful substance will leave the room with the air: $dm_2 = C \cdot v \cdot dt$. The difference between these values will be $W \cdot dC$.

The material balance equation will, therefore, be as follows:

$$dm_1 - dm_2 = W \cdot dC \quad (10)$$

or

$$C_0 \cdot v \cdot dt - C \cdot v \cdot dt = W \cdot dC \quad (11)$$

hence

$$\frac{v}{W} dt = \frac{dC}{C_0 - C} \quad (12)$$

At $t = 0$ also $C = 0$ and after integrating the equation we get the concentration after time t :

hence

$$\frac{v}{W} \int_0^t dt = \int_0^C \frac{dC}{C_0 - C}; \quad \frac{v}{W} t = \ln \frac{C_0}{C_0 - C} \quad (13)$$

$$C = C_0 \left(1 - e^{-\frac{v}{W} t} \right)$$

Equation (13) characterizes the buildup of pollutant concentrations in a room over time and is graphically depicted in Fig. 6 below.

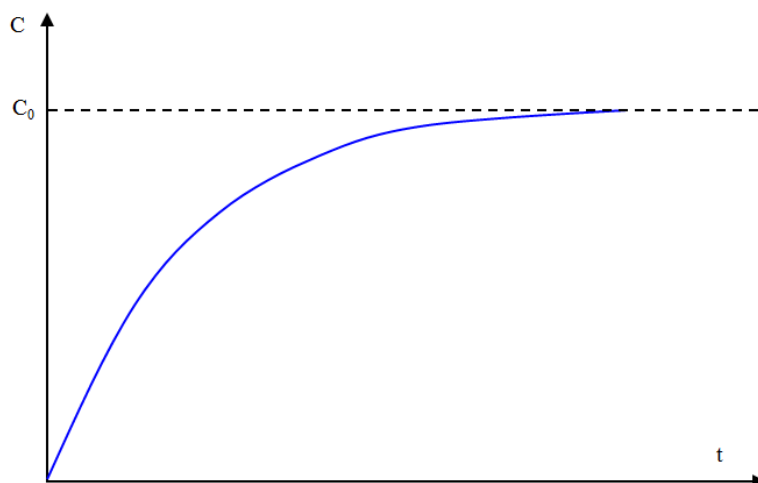


Fig. 6. Nature of change in concentration of noxious admixture over time - in an unventilated room.

Transforming equation (12) we get:

$$\frac{dC}{dt} = \frac{v}{W} (C_0 - C) \quad (14)$$

Equation (14) shows that the rate at which a given concentration is reached indoors is proportional to the v/W ratio.

The limiting concentration, close to C_0 , is established very slowly. Thus for we obtain::

$$\frac{v}{W} t = 3 \text{ hence } t = \frac{3W}{v}$$

eg. at $v = 0,3 \text{ m}^3/\text{min}$ i $W = 20 \text{ m}^3 \rightarrow t = 200 \text{ min}$

In the case of ventilated rooms, the material balance of harmful admixture in the room is somewhat complicated, because in this case a different amount of admixture is removed from the room during dt than in the case of unventilated rooms.

This amount is:

$$dm_3 = C(V - v)dt \quad (15)$$

where: V is the volume of purified air fed into the room by the filter unit per unit time.

This is why:

$$\text{or} \quad dm_1 - dm_3 = W \cdot dC \quad (16)$$

$$C_0 \cdot v \cdot dt = C(V + v)dt = W \cdot dC \quad (17)$$

Hence:

$$C = \frac{v}{V + v} C_0 \left(1 - e^{-\frac{V+v}{W}t} \right) \quad (18)$$

In this case, as a result of the operation of the filtering device, the room after a certain period of time will establish a limiting concentration of harmful admixture less than C_0 , because at the $t \rightarrow \infty$

$$C_{gr} = \frac{v}{V + v} C_0 \quad (19)$$

It follows that always $C_{gr} < C_0$.

If the rate of inflow of contaminated air v into the room is high, and the ventilation rate V does not secure the maintenance of positive pressure in the room, then, as can be seen from the formulas given, the concentration of the harmful substance in the room can quickly rise to a dangerous value.

For example, with $v = 0.3 \text{ m}^3/\text{min}$; $V = 1 \text{ m}^3/\text{min}$; $W = 20 \text{ m}^3$ and $t = 10 \text{ min}$ then according to formula (18):

$$C = \frac{0,3}{1,3} C_0 (1 - e^{-0,65}) = 0,11 C_0$$

For an unventilated room at the same time

$$C = C_0 (1 - e^{-0,15}) = 0,14 C_0$$

For highly toxic poisonous agents, C should be significantly less than C_0 .

With $C \ll C_0$ also $C/C_0 \ll 1$, which is possible when $v/W \ll 1$.

Therefore, it can be assumed that:

$$e^{-\frac{v}{W}t} = 1 - \frac{v}{W}t \quad \text{or} \quad e^{-\frac{V+v}{W}t} = 1 - \frac{V+v}{W}t \quad (20)$$

$$C = C_0 \frac{v}{W}t$$

Equation (20) shows that, theoretically, the concentration of any harmful admixture in a room is directly proportional to the external concentration C_0 , the amount of air penetrating through the leaks per unit time v , the penetration time t , and inversely proportional to the volume of air in the room W .

However, in reality, the external concentration C_0 will not be constant for the entire time t , but will decrease, the value of v may also change in time both ways, because it depends on the pressure difference Δp and the degree of hermeticity of the room.

However, in reality, the external concentration of C_0 will not be constant throughout time t , but will decrease, the value of v can also vary over time both one way and the other, as it depends on the pressure difference Δp and the degree of hermeticity of the room.

As a result of the sorption of harmful substances on the structural materials of the room, equipment, uniforms, the concentration of C inside the room will always be less than that calculated from the given formulas.

To determine the concentration of the noxious substance in the room according to formulas (18, 19, 20), it is necessary to know the value of v , which, in turn, can be calculated only if the total cross-section of the cracks is known, which is very difficult, or rather impossible, in practice. Therefore, for practical purposes, it is more convenient to introduce the concept of the permeation coefficient, which is the ratio of the concentration of the harmful substance in the room (after time t) to the external concentration, expressed as a percentage:

$$K_p = \frac{C}{C_0} \cdot 100\% \quad (21)$$

It is necessary to distinguish between partial and overall transmission coefficients. If the object has several sequentially distributed sealing elements, protecting the main room from the penetration of scaled air, then in this case the overall transmission coefficient for the whole object is equal to the product of the partial coefficients:

$$K_p = K_{1p} K_{2p} K_{3p} \dots K_{ip} \quad (22)$$

According to equations (13, 18, 20), the concentration of the harmful substance C in the room will increase at time t and the permeation coefficient K_p will increase accordingly over time.

Therefore, the transmission coefficient for objects or individual structural elements should always be referred to a specific time.

As an approximation, the permeation coefficient K_p for time t theoretically according to equation (20) is equal to the ratio of the total amount of permeated air at that time $v \cdot t$ to the volume of the room W expressed in percentage:

$$K_p = \frac{v \cdot t}{W} \cdot 100\% \quad (23)$$

The last equation provides an approximate estimate of the total amount of air penetrating the object. If the permeation coefficients and the volume of the object are known.

Determination of the permeation coefficient in practice is also a difficult task due to the need to produce an adequate external concentration of the harmful substance and the analysis of its small concentrations inside objects.

Therefore, it is expedient to introduce the concept of the so-called permeation coefficient, expressing the ratio of the permissible total dose $(\Sigma Ct)_d$ to the total dose acting on the object $\Sigma C_0 t$:

$$K_{pd} = \frac{(\sum C \cdot t)_d}{\sum C_0 \cdot t} \quad (24)$$

where :

C - concentration of the harmful substance inside the room in g/m^3 ;

C_0 - external concentration of this substance in the air g/m^3 ;

t - time in minutes.

As an approximation, the following values of permittivity can be assumed:

- for highly toxic CW vapors:

$$\text{sarin } K_{pd} = 1 \cdot 10^{-3}$$

$$\text{soman } K_{pd} = 1 \cdot 10^{-4}$$

- for radioactive aerosols $K_{pd} = 1 \cdot 10^{-2}$.

Knowing the permissible penetration rate, it is possible to determine the permissible amount of contaminated air penetrating the facility:

$$v_d = K_{pd} \frac{W}{t} \quad [\text{m}^3/\text{min}] \quad (25)$$

By substituting the value of K_{pd} we get:

- at the penetration of highly toxic CWs:

$$v_d = 1 \cdot 10^{-3} \div 1 \cdot 10^{-4} \frac{W}{t} \quad (26)$$

- at the penetration of radioactive aerosols:

$$v_d = 1 \cdot 10^{-2} \frac{W}{t} \quad (27)$$

To evaluate the permissible permeation time t_d , it is necessary to know the permissible permeation rate, the volume of the room and the volume of permeated air. The permissible permeation time approximately is, thus:

- for permeation of highly toxic vapors CW:

$$t_d = 1 \cdot 10^{-3} \div 1 \cdot 10^{-4} \frac{W}{v} \quad (28)$$

- at the penetration of radioactive aerosols:

$$t_d = 1 \cdot 10^{-2} \frac{W}{v} \quad (29)$$

It should be borne in mind that in calculating v_d and t_d , the assumption was made that the infiltrated contaminated air would immediately mix with the indoor air. In reality, this assumption cannot be fulfilled, especially in the case of rooms with a large capacity. In such cases, when evaluating the permissible permeation time, it is necessary to consider not the entire volume W , but only that part of it where air is most likely to mix.

4.2 Ways to protect facilities from the penetration of contaminated air [20]

It is very difficult to remove completely the phenomenon of penetration of contaminated air into facilities. To achieve this, it would be necessary to ensure absolute tightness of the facilities, which is practically impossible. Therefore, it is necessary to strive to reduce the amount of air penetrating into the facility as much as possible.

This can be achieved by way of:

- sealing and closing any openings and gaps created during construction;
- construction of airtight vestibules in the entrances, giving several degrees of sealing;
- creating a certain positive air pressure in the shelter, counteracting the penetration of contaminated air through leaks.

Sealing of facilities due to highly toxic CW, RS and biologicals must meet high requirements.

Taking into account the purpose of the facility, the probable duration of action of toxic agents, radioactive agents and biological aerosols, as well as the possibility of the existence of periods of full isolation (when the filtering device does not work or operates in a recirculation regime), it should be assumed in relation to field facilities that the tightness of the shelter should ensure the maintenance of an overall penetration rate K_p of no more than 1.10-3% during the following time:

	summer	winter
- shelter	15 – 20 min	do 10 min
- light shelter	30 - 60 min	do 20 min
- heavy shelter	60 – 120 min	do 30 min

In shelters of the stationary type, the sealing requirements should be even higher and the time to maintain the value of $K_p = 1 \cdot 10^{-3}\%$ much longer.

Insulation of the facility is achieved by sealing the following elements of the facility:

- inputs;
- functional openings (gunports, places of entry of various pipes, cables, etc.);
- surfaces of separating elements (ceilings and walls).

The most serious difficulty in sealing facilities is the sealing of entrances. This involves the fact that through the entrance the object connects with the surrounding atmosphere when the door is opened.

The idea of sealing entrances is to create several airtight partitions with minimal natural leakage and buffer spaces where dilution of infiltrated contaminated air would occur.

In addition to this, provision should be made to ventilate these spaces with air coming out of the shelter in order to periodically purify the air in them. The movement of air in doing so should be in the direction of the contaminated atmosphere. The realization of this idea is achieved by building atria with airtight partitions and airtight doors.

The number of vestibules depends on the purpose, volume and type of facility. In simple, small facilities, there may be one vestibule with two airtight doors. In large and important facilities, there may be more vestibules. The more vestibules in an entrance, the higher its degree of airtightness, the lower the probability of penetration of contaminated air through the entrance and the longer the time of full isolation of the facility (the period of time during which the filtering device is not operating).

However, increasing the number of vestibules increases the consumption of materials, time and manpower, and complicates the operation of facilities. Therefore, in practice, the number of vestibules is limited to minimally unnecessary (most 5).

Let's try to quantify the value of vestibules in reducing the phenomenon of penetration of contaminated air.

Let's consider the penetration of contaminated air into an object having different numbers of atria. According to equation (13), the concentration after time t will be:

- in the first atrium:

$$C_1 = C_0 \left(1 - e^{-\frac{v_1 \cdot t}{W_1}} \right) \quad (13a)$$

- in the second vestibule

$$C_2 = C_1 \left(1 - e^{-\frac{v_2 \cdot t}{W_2}} \right) \quad (13b)$$

- in the n th vestibule

$$C_n = C_{n-1} \left(1 - e^{-\frac{v_n \cdot t}{W_n}} \right) \quad (13c)$$

- in the shelter

$$C_{sch} = C_n \left(1 - e^{-\frac{v_{sch} \cdot t}{W_{sch}}} \right) \quad (13d)$$

where:

C_0 - external concentration of the harmful substance;

$V_1, V_2, \dots, V_n, V_{sch}$ - volume of infiltrated contaminated air per unit time in the 1st, 2nd...nth atrium and shelter, respectively;

$W_1, W_2, \dots, W_n, W_{sch}$ - volume of the 1st, 2nd, ..., nth vestibule and shelter, respectively.

Air overpressure in the shelter can be created by emitting compressed air from cylinders, heating the indoor air and mainly by running the filtering device.

The positive air pressure inside the facility is called the support and is expressed in mm of water column (now in Pa) - 1 mm of water column = 9,81 Pa.

If there is positive pressure in the shelter, then air flows continuously to the outside through the leaks, and in this case external contaminated air cannot penetrate the shelter.

In sealed field shelters, overpressure is created almost immediately when the filtering device is activated and immediately decreases when it is turned off.

The amount of overpressure depends on:

- the tightness of the facility;
- the capacity of the filtering device or the amount of air emitted from the cylinder.

For any facility with constant airtightness, the positive pressure is a function of the airflow of the filter unit:

$$\Delta p = f(V)$$

In practice, it is important to know the value of the required support. In the general case, the support should exclude the possibility of penetration of contaminated air into the object. Therefore, its value should slightly exceed the maximum possible for the object in question operating differential pressure.

For stationary objects, subject to the action of wind, the support should be not less than 5 mm of water column (in practice, about 100 -200 Pa).

For objects that are not affected by wind, a support of 1-2 mm of water column is sufficient (practically 300 - 400 Pa).

In practice, the size of the support can be adjusted automatically by using appropriate valves, regulating the rate of air flow out of the object.

4.3. Ventilation of facilities [20]

Objects intended for collective protection should be designed for a relatively long-term stay of people in them, for whom adequate sanitary and hygienic conditions must be provided.

Violation of certain sanitary and hygienic norms of the facility leads to a decrease in the fitness of people, causes disease, and in some cases can lead to poisoning. The reason for the violation of normal sanitary and hygienic conditions in the premises is the lack of clean air, or more precisely - the violation of its normal composition.

It is known that in unventilated rooms with many people, the air after some time becomes unfit for breathing. It is therefore necessary to continuously supply the facility with a certain amount of clean air. If the outside air is contaminated, it should be cleaned in advance in special filter absorbers.

The need to ventilate facilities is also related to the removal of toxic vapors and gases (carbon monoxide and dioxide, acrolein, sulfur oxides, ammonia, fat decomposition products, etc.), as well as excess moisture and heat.

5 Summary

The problem of air pollution is now becoming a worldwide issue. It is known that atmospheric pollution is the cause of many diseases, including cancer, and a significant deterioration in the quality of life. The hypothetical threat to the national territory, along with technical and technological development, of contamination by substances of

industrial origin is increasing. These will be chemical and radioactive substances, and biological ones cannot be ruled out. The 21st century, unfortunately, is full of war conflicts, unfortunately with weapons of mass destruction, but also strikes against elements of industrial infrastructure. The war in Ukraine proves that the Russians can provocatively use any weapon to achieve political and propaganda goals. The banned phosphorus munitions have already been used.

Armed forces should be adequately prepared to protect soldiers, and emergency response units should be prepared to protect the population, that is, to provide the conditions necessary to protect human life and health and ensure basic survival conditions in emergency situations. Certainly, such protection will not be provided by places of temporary shelter and concealment as defined by the State Fire Service [21]. In the cited publication FM 3-11.4, for ad hoc (temporary) facilities, it is recommended to seal selected parts of the building with temporary measures, such as plastic sheeting, tape, sandbags, etc., additional sealing enclosures, such as in the form of portable interior enclosures or a lining system to improve their tightness.

Virtually only shelter-type facilities (a shelter is a protective structure with a structurally closed, airtight enclosure that provides protection for people, equipment, material stockpiles or other material goods against assumed agents of destruction acting from all sides. They must have improved protective characteristics against conventional attacks and WMD strikes) can provide protection against the penetration of agents harmful to health and life.

According to NATO's views, protection of objects from TIM penetration is made difficult and complicated by the fact that military absorbers (filter absorbers) have limited protection time against TIM. Practically, there is no universal absorber for all TIM, they are selective for certain groups, for example. Multigas filter absorber type A2B2E2K2-P3 - A2 - organic gases up to 0,5% V/V; particles with min 99,95% efficiency; B2 - inorganic gases, without CO up to 0.5% V/V and particles; E2 - sulfur dioxide and acid gases up to 0.5% V/V and particles; K2 - ammonia and organic derivatives of ammonia up to 0,5% V/V and particles.

It is very difficult to remove completely the phenomenon of penetration of contaminated air into objects. It is practically impossible to achieve complete airtightness of the object, so it is necessary to strive to reduce the amount of air penetrating into the object as much as possible.

This can be achieved by:

- seal and close any openings and gaps created during construction;
- building airtight vestibules in the entrances, giving several degrees of sealing;
- creating a certain air overpressure in the shelter, counteracting the penetration of contaminated air through leaks;
- insulation with replenishment of air from the facility's reservoirs with simultaneous regeneration.

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